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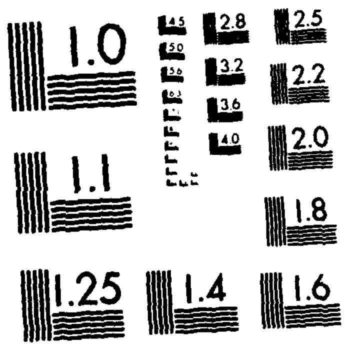

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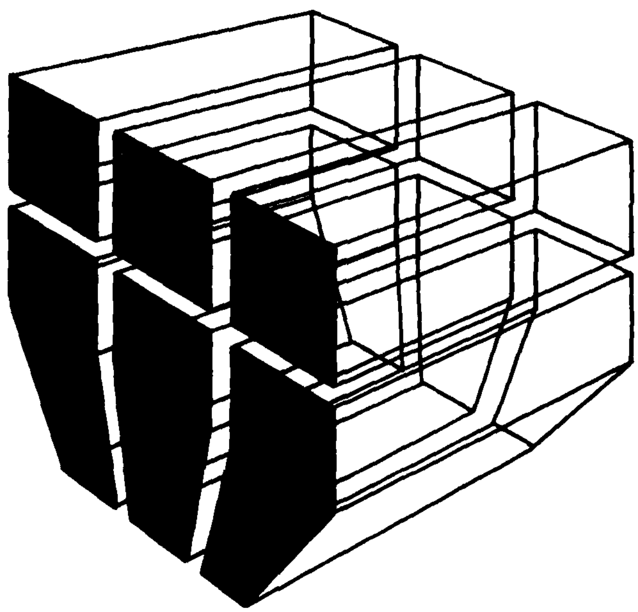
TECHNICAL REPORT E-86/04
May 1986
Energy Storage for Facility Energy Systems

Assessment of Energy Storage Technologies for Army Facilities

by
R. J. Kedl
C. W. Sohn



This report assesses energy storage concepts having potential applications to Army facilities. Commercially available thermal, mechanical, and electrical storage systems are described. Use of such systems could benefit the Army in the general areas of electric load management, energy conservation, and/or increased capacity of installed heating, ventilating, and air-conditioning equipment.

Potential storage applications were ranked and tabulated with respect to anticipated economic feasibility, ranging from most to least attractive. Based on this analysis, a diurnal cold storage system for electrical load management was recommended for an energy storage demonstration project at an Army installation.

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Potential storage applications were ranked and tabulated with respect to anticipated economic feasibility, ranging from most to least attractive. Based on this analysis, a diurnal cold storage system for electrical load management was recommended for an energy storage demonstration project at an Army installation.

FOREWORD

This research was conducted for the Office of the Assistant Chief of Engineers (OACE) under project 4A162781AT45, "Energy and Energy Conservation"; Technical Area D, "Energy System/Alternate Sources"; Work Unit 005, "Energy Storage for Facility Energy Systems." The work was performed by Mr. R. J. Kedl of the Oak Ridge National Laboratory (ORNL) under the direction of the Energy Systems Division (ES), U.S. Army Construction Engineering Research Laboratory (USA-CERL). Mr. B. Wasserman, DAEN-ZCF-U was the OACE Technical Monitor.

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Mr. R. G. Donaghy is Chief of USA-CERL-ES. COL Paul J. Theuer is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

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ASSESSMENT OF ENERGY STORAGE TECHNOLOGIES FOR ARMY FACILITIES

1 INTRODUCTION

Background

As part of a national effort, the Department of Defense is examining ways to reduce energy consumption and costs at its permanent facilities. Energy storage, a technology that is central to many conservation applications, may be used when energy is available, but is not yet required. Energy may be stored in a number of different forms, the most common being thermal energy. For example, heat (or cold) may be stored as hot water (or cold water) for building space conditioning. There are several forms of mechanical energy storage, such as compressed air and flywheels. Electrical energy may be stored in batteries. Still other storage technologies are chemical storage, hydrogen storage, and superconducting magnetic storage.

Stored energy can be used in a variety of applications, which fit into the following three categories:

1. Electric Load Management: Energy storage can reduce peak daytime electricity demand and transfer its use to off-peak times when its cost is more favorable. For example, chillers may be operated at night to generate cold water or ice, which can be stored and used the next day for air conditioning.

2. Energy Conservation: Waste heat may be recovered from a hot effluent stream and stored for subsequent use. Examples are post laundries, central dining hall kitchens, and reject heat from chillers. Applications are building heating, district heating, hot water for showers in barracks, and cleaning operations in dining facilities. The storage cycle for these examples is diurnal, but annual cycle storage can also be applied. An example would be the capture and storage of winter chill as either cold water or ice, to be used the following summer for air conditioning. The cold water may be stored underground in a natural aquifer.

3. Increasing the Capacity of HVAC Equipment: The cooling capacity of an air conditioner may be increased by operating the system at its rated capacity during periods of low demand (at night), and storing the excess capacity as cold water. The following day, the stored cold water may be used to assist the chiller, thus increasing system capacity. For certain situations, the chiller capacity may be doubled, both in terms of peak cooling demand and total daily cooling, by adding storage.

Thermal energy storage is widely used in Europe, where the cost of energy has been traditionally higher than in the United States. It is used for both electric load management and conservation. Energy storage has not been used extensively in past years by any sector in the United States (residential, commercial, institutional, or industrial). Recently, however, because of increased awareness of energy cost, the use of storage is increasing and many new and retrofit installations have been built.

Objective

The objective of this report is to describe and assess present and near-term storage technologies, and to qualitatively rank storage technologies and applications with respect to new and existing Army facility energy systems.

Approach

Literature on energy storage and its applications was analyzed to summarize data on storage technologies and identify and rank the storage applications in a manner usable to planners at permanent Army facilities.

Scope

Advanced storage technologies such as chemical storage, hydrogen storage, and superconducting magnetic storage are not treated in this study. Also, storage specifically for solar energy is not discussed, although many of the storage units described would be equally appropriate for both solar applications and load management and conservation applications.

Organization of Report

Chapters 2 and 3 describe concepts of energy storage and currently available energy storage technologies, and Chapter 4 focuses on the application of energy storage to building energy systems. Chapter 5 discusses postwide application of energy storage and assesses various energy storage applications with respect to economic feasibility and availability of technology. Chapter 6 provides an analysis of energy storage and technology, and Chapter 7 gives conclusions and recommendations based on the analysis.

Mode of Technology Transfer

It is recommended that information in this report be condensed into an Engineer Technical Note (ETN) introducing energy storage as a way to reduce Army facility energy consumption and costs. This ETN will serve as the basis for selecting energy storage systems at Army facilities.

2 DESCRIPTION OF DIURNAL CYCLE STORAGE

This chapter and Chapter 3 describe various energy storage technologies, including their application in terms of energy source and energy use, level of development and commercialization, advantages and disadvantages over alternate storage systems, available sizes and capacities, cost, auxiliary equipment that may be required, especially for retrofit, and, when possible, results of any documented customer satisfaction studies. Current R&D efforts that appear to have near-term and beneficial consequences for a storage concept are noted. Emphasis is on storage systems that are available commercially, and on concepts that are sufficiently well developed and attractive that a demonstration project has been started.

The major classification of technologies described in Chapters 2 and 3 is by cycle time. Diurnal storage systems are discussed first, followed by annual cycle storage systems. Within the diurnal cycle category, thermal energy storage systems are described first, followed by mechanical energy storage systems and electrical energy storage systems. All storage concepts in the annual cycle category are thermal.

Thermal Energy Storage Systems

Sensible Heat and Cold Storage (Including Ice)

The most obvious way to store thermal energy is to heat the storage medium to a high temperature (heat storage) or to cool it to a low temperature (cold storage). This is referred to as "sensible" heat storage; the storage medium's heat capacity is the physical property used for storage. The amount of stored heat or cold is:

$$Q = M\ Cp\ (T_c - T_o) \qquad \text{[Eq 1]}$$

where:

Q = total amount of useful heat or cold that is stored (Btu)
M = total mass of storage medium (lb)
Cp = heat capacity of storage medium (Btu/lb-°F)
T_c = temperature of the storage medium in its charged state (°F)
T_o = temperature of the storage medium in its discharged state (°F).

In using this formula, note that Q is positive for heat storage and negative for cold storage. Note also that T_o is not ambient temperature, but rather the temperature of the storage medium when its useful heat or cold has been extracted.

Any material may be used for sensible heat storage. However, only a few materials have developed serious technical and commercial application (Table 1). The table also indicates materials that are commonly used today, as well as those that have been seriously considered for storage, but are not yet commonly used, or those used only for very special storage applications. Of the materials listed, only water is used for both heat and cold storage; the rest are used only for heat storage.

Although storing cold as ice is, strictly speaking, a form of latent storage, it is discussed with sensible storage, because cold water storage and ice storage are closely related.

Table 1

Materials Used for Sensible Heat Storage

Material	Typical Storage Temperature (°F)	Heat Capacity (Btu/lb-°F)	Soild Density (lb/cu ft)	Volume Storage of Solid* (Btu/cu ft-°F)
		In General Use Today		
Water	210	1.0	61.0	61
Pressurized water	300	1.0	60.2	60
Chilled water	35	1.0	62.4	62
Olivine bricks	1500	0.24	165	40
Magnesite bricks	1500	0.27	185	50
Concrete (floor)	100	0.21	140	29
Rocks (limestone)	180	0.25	165	41
		Seriously Considered But Not in General Use		
Rock (limestone)	1000	0.25	165	41
Slag	1500	0.25	130	32
Heat transfer oils**	600	0.60	43	26
Heat transfer salts***	950	0.37	110	41

*Assumes solid fraction of storage medium is 1.0.
**For example, Caloric HT-43 (Exxon Corp.).
***For example, Hitec (DuPont Chemical Co.); 40 percent $NaNO_2$, 7% $NaNO_3$, 53 percent KNO_3.

Water Storage Systems (Including Ice). Water is the most widely used storage material for heating and cooling buildings. The heat capacity of water is one of the highest of any material, thus allowing a relatively compact sensible heat storage system. Water is cheap and readily available, and its properties and handling characteristics are well known. Materials and equipment for water-handling systems are readily available from numerous sources. Water can be used for heat, cold, or combined storage. For heat storage, the maximum temperature is limited to about 210°F‡ for unpressurized systems and about 300°F for moderately pressurized systems (55 psig). For cold storage, the minimum temperature is limited to about 35°F to prevent ice formation.

A 1980 survey [1]‡‡ identified about 300 commercial buildings in the United States and Canada that use some form of thermal energy storage for building heating and cooling applications. This survey covered an estimated 50 to 90 percent of the total storage installations in place at that time. Of the installations in the United States, 75 percent use water (or ice) as the storage medium. About 30 percent of the installations use water for heat storage in either pressurized or unpressurized systems, 21 percent use

‡Metric conversion factors are provided on p 89.
‡‡Numbers in brackets refer to references beginning on p 90.

water for cold storage either as cold water or ice, and 22 percent use water for combined heat and cold storage. The purpose of the storage is to improve the daily electric load profile. This involves either shifting the electric load to off-peak periods if the building is on a time-of-use rate structure, or reducing the peak daytime demand if the building is on a demand rate structure, or both. In some cases, hot water for storage is generated by recovering waste heat from the chiller condenser. Buildings with storage for solar applications were not included in the survey.

Buildings on Army posts are heated almost exclusively with natural gas and oil, which are not normally subject to a time-of-use or demand rate schedule. Therefore, there seems to be little incentive for heat storage. However, air conditioning is by electric equipment, and most large buildings have a substantial cooling load. Thus, water or ice storage for air conditioning and for electrical load management may be of considerable interest for military applications.

There are four general storage system types for cold water storage at large installations [2]: membranes, multiple tanks, baffled tanks, and natural stratification (Figures 1 through 4). The main purpose of each method is to prevent mixing of cold water generated by the chiller with the warmer water already in the tank or returning from the building cooling system. Although the emphasis is on cold water storage, the same storage system types may be used for hot water storage.

Membrane storage (Figure 1) uses a coated fabric membrane or sock fitted to the tank to separate cold water from warmer water. Cold water is stored in a single tank below the membrane and return water above; thus, the membrane moves up as the tank is charged and cold water displaces warm water, and then moves down as cold water is used and displaced with warmer water. A number of storage installations have been equipped with membranes for hot and cold water storage. One large installation in Toronto, Canada, has two 250,000-gal (946-m^3) tanks, each equipped with a membrane.

In multiple tank storage (Figure 2), the cold water and warmer water are stored in separate tanks. The tank farm contains one more tank than is required for storage. To charge the system, water is drawn from a tank of discharged water, cooled by the chiller, and added to the empty tank. In the discharge mode, cold water is drawn from a cold tank, used for space cooling, and placed in a warm water tank. Thus, the tank farm always contains one empty tank or two partially empty tanks.

Disadvantages of multiple tank storage are the lost storage volume resulting from the extra tank, and the complex control system and valve arrangement required to properly route the water to and from the proper tanks. Construction costs would probably be higher than for other water storage systems because of the large number of valves and amount of piping required.

The advantage of the multiple tank storage system is its flexibility. The tanks used for cold storage or hot storage at different times of the year can be changed simply by changing the valve sequencing.

Many multiple tank storage systems have been installed. The largest--at an IBM manufacturing and laboratory facility in Tucson, AZ--has about 2,400,000 sq ft of floor space and more than 10,000 tons of air conditioning. Storage is in twenty-one 300,000-gal above-ground steel tanks. Both hot and cold water are stored. The source of hot water is a heat-recovery unit on one of the five chillers. The storage system is computer-controlled and became operational in 1979.

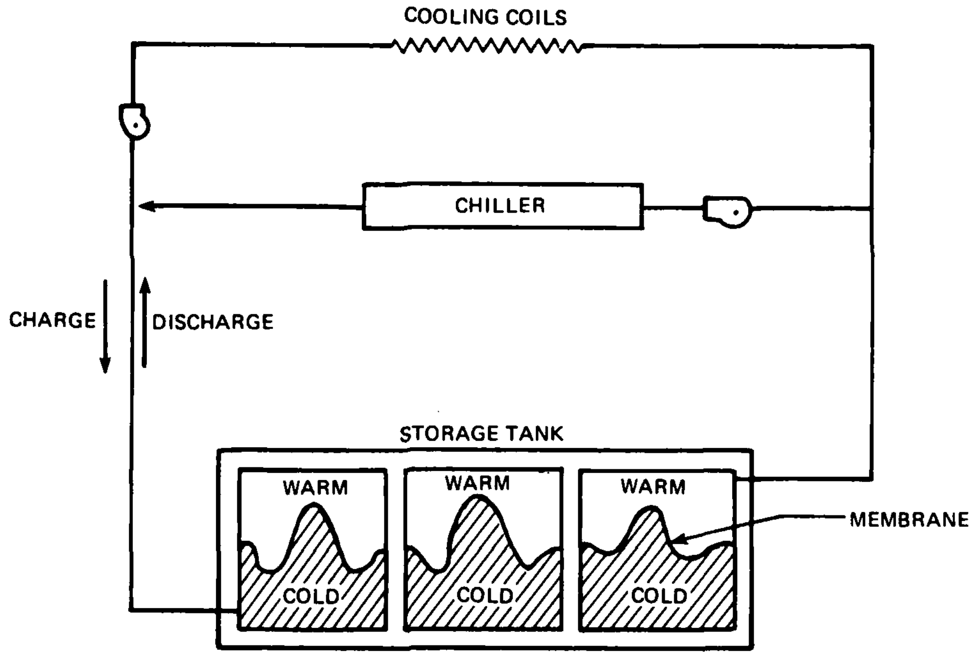

Figure 1. Membrane storage of chilled water.

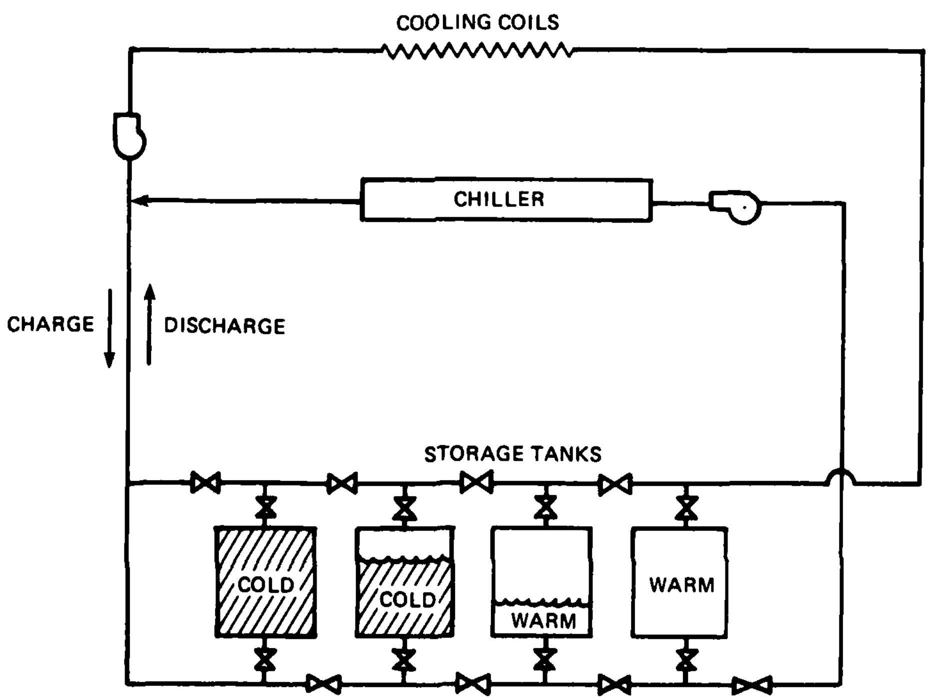

Figure 2. Multiple tank storage of chilled water.

Baffled tank storage (Figure 3) implies the use of baffles to prevent mixing in the storage tank. Conceptually, natural thermal stratification can best be achieved in a tall narrow tank because the mixing volume at the interface is small compared to the total tank volume. The baffle arrangement shown in Figure 3 can be envisioned as a scheme that conceptually makes a tall narrow tank out of a short wide tank. The arrangement shown was developed by the Japanese, where it has been estimated [2] that hundreds of these storage tanks have been installed. A few installations with this arrangement have been built in the United States. One such installation built in the new Mechanical Engineering Building at the University of New Mexico featured baffles following the Japanese design. After extensive testing [4] as both hot and cold water storage tanks, it was concluded that better stratification was achieved by removing the baffles and installing a carefully designed diffuser system to provide natural stratification. The two major problems that negated the benefits of baffling were excessive heat transfer across the uninsulated baffles and leakage between chambers where baffles joined the tank wall.

Natural stratification (Figure 4) uses the slightly lower density of warm water to cause it to "float" on the more dense cold water. Because the density difference is not great, natural stratification is difficult to achieve, especially for cold water storage. For example, if the charged cold water temperature is 40°F and the discharged cold water temperature is 60°F, then the difference in density between the two is only about 0.1 percent. In this example, 40°F was chosen because the density of water is a maximum at this temperature. It may not be possible to maintain the cold side of a thermocline at temperatures lower than 40°F. Alternately, if the charged hot water temperature is 160°F and the discharged hot water temperature is 110°F, the difference in density is about 1.3 percent, or more than 10 times that for cold water storage. To achieve successful stratification, the inlet manifold must be designed to inject water uniformly across the tank and at very low velocities to prevent mixing.

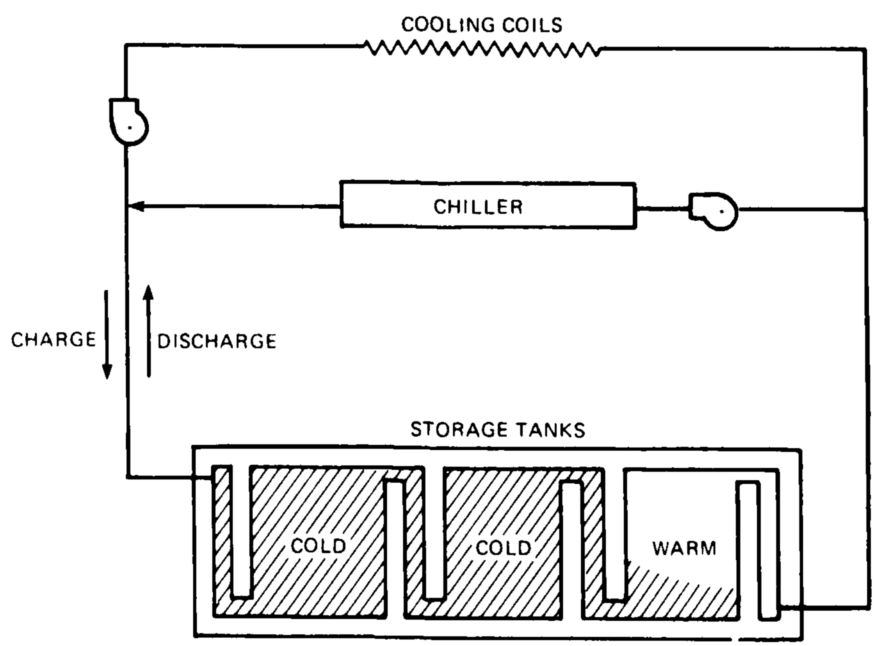

Figure 3. Baffled tank storage of chilled water.

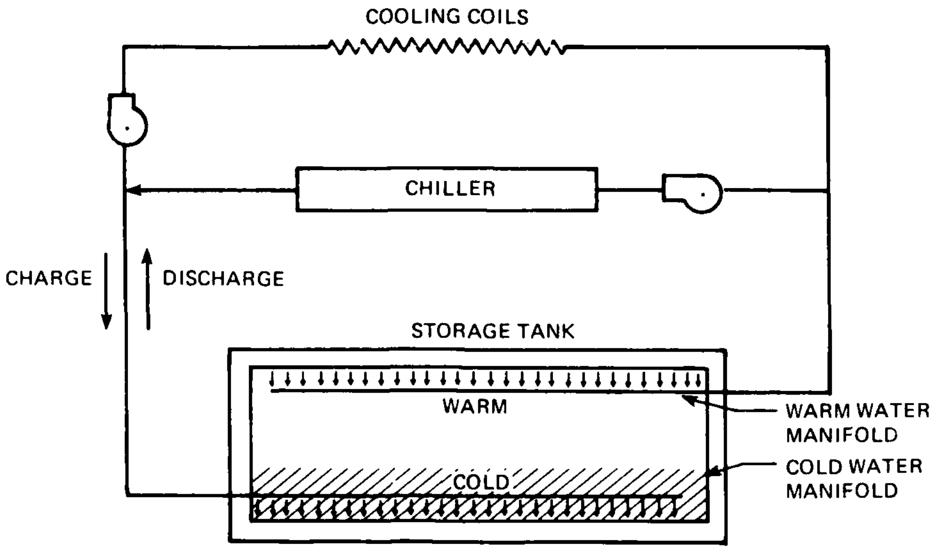

Figure 4. Natural stratification storage of chilled water.

While several naturally stratified installations have been built in the United States, not all of them have been successful. In one succcessful installation at Stanford University, cold water is stored in a 4,000,000-gal underground tank. The cold water inlet manifold consists of a grid of 4-in. pipe covered with rock to achieve the desired flow characteristics. The water depth in the tank is 24 ft. Measurements indicate that the thermocline is only about 3 ft thick.

Recent advances in understanding the dynamics of natural stratification[2,3,5] have increased confidence in the ability to design a successful installation.

Ice storage systems are the competition for cold water storage systems. The heat of fusion for water is 144 Btu/lb. This means that 1 lb of water will store 144 Btu of cold as it freezes, but only store 20 Btu of cold between 35° and 55°F. Thus, ice storage units are much more compact than cold water storage units.

Figure 5 shows the most common ice maker for cold storage. Tubes are supported in a serpentine fashion throughout a tank filled with water. The tubes act as an evaporator for the chiller cycle, so that ice forms as a log around the tubes. Tube spacing is such that the radial ice thickness around the tube is about 2.5 in. when fully charged. The thermal resistance caused by the ice requires the refrigerant temperature to drop as the ice thickness increases. At full charge, the refrigerant temperature is estimated to be about 10°F. Controls are used to prevent the ice logs from bridging and thus maintaining flow passages through the storage unit. In the fully charged state, a little more than half the total water in the storage tank is frozen. Cold is extracted by pumping water through the ice logs. Agitation or baffling for flow control is required to prevent short circuiting and to keep the water in contact with the ice. Agitation can be accomplished by bubbling air through the storage tank. Standard units are available commercially [6,7,45] with capacities up to 100,000 lb of ice (1200 ton-hours).

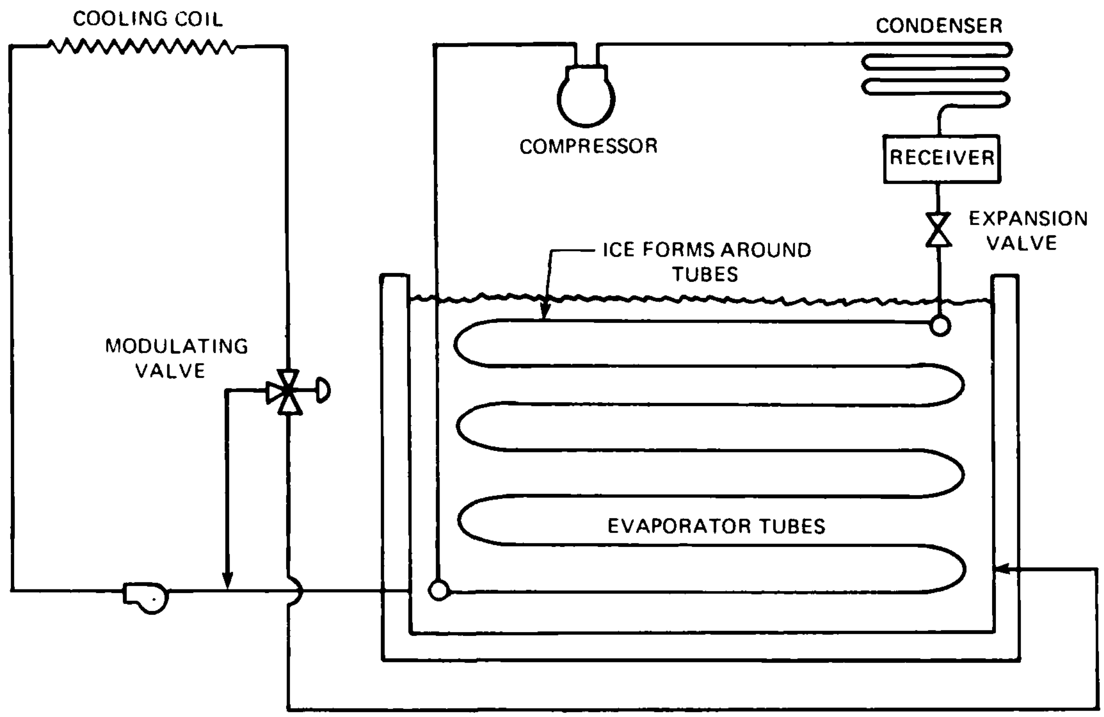

Figure 5. Cooling system using ice for cold storage.

Larger storage capacities can be achieved with multiple units or by a custom-designed, field-erected installation. One of the largest known ice storage installations is at a Union Oil Co. of California Research Center in Brea, California. The building contains 420,000 sq ft of conditioned space. The storage installation consists of 11 tanks, each of which contains 100,000 lb of ice at full charge. Thus, the total storage capacity is 1,100,000 lb of ice. The chillers generate this ice during a 12- to 14-hour period, primarily during off-peak hours.

Other manufacturers [10,45] use a somewhat different technique. An antifreeze solution is pumped through a heat exchanger placed in the water tank to charge and discharge the storage unit. The tubes are plastic and much closer together than in the previous storage concept. Since the water does not have to be pumped through the ice side of the storage unit, it can be frozen completely, thus increasing the volumetric storage density. However, the system requires an additional heat exchanger for the intermediate loop. Standard units with latent storage capacities up to 1,000,000 Btu (83 ton-hours) are available. Larger storage requirements are met with multiple units. One such installation has a tank farm of 10 units with space for two additional units if needed.

An alternate form of ice-maker is often referred to as a dynamic ice system or an ice shucker. In one arrangement of this system, the evaporator is in the form of a flat plate which is held vertical. Water is sprayed on the plate and freezes to form a layer of ice. Periodically, condenser heat is routed through the evaporator to release the ice that falls into a bin below the evaporator. Cold is extracted from the ice by pumping water through the ice storage chamber. Shucker ice-makers are available with capacities of up to 80 tons [11]. The ice storage bin must be sized for the installation. Its main problems are ice packing density, defrost controls, and pumping energy for spray. There are no known installations of the shucker for cooling buildings other than Federally funded demonstrations.

The discussion so far has summarized cold water and ice storage installations for air-conditioning applications in large buildings. Cold storage may also be used for residential and small commercial applications. To resolve issues on the applicability of energy storage in the residential sector for electric load management, the Department of Energy cofunded, with participating utilities, an extensive test program. Ten projects were conducted: five involved heat storage [12], and five involved cold storage [13]. The objectives of these studies were to (1) collect reliable load research data, (2) delineate and solve installation problems, (3) evaluate maintainability, (4) determine customer and utility acceptance, and (5) develop cost data. The major thrust of this project was to evaluate the utilities' vewpoints of heat and cold storage in the residential sector as a load management tool. Table 2 summarizes the five cold storage projects.

Data were collected during the 1980 cooling season. Two utilities collected additional data during the 1981 cooling season. All the storage systems were the ice-making type. Three can be characterized as the direct expansion type, in which the evaporator coil is immersed in the water. One system had an intermediate heat exchanger that served as the evaporator. An antifreeze solution was chilled in this heat exchanger and then circulated through tubes in the storage tank. None of the storage equipment could be considered as fully commercial and would best be described as prototypical. Each manufacturer did have field experience with this kind of equipment, and supplied a warranty on the storage unit for the rest of the test. None of the cold storage installations were packaged systems. Rather, the storage tank and the associated mechanical and controls package were designed as a unit that was then mated to standard off-the-shelf residential air-conditioning condensing units. Most of the storage equipment was designed for full storage; that is, the daytime cooling load of the residence was met entirely by storage, and the air conditioner did not operate during peak periods. Half of the Wisconsin Electric Power Company's test homes operated their storage equipment in the partial-storage mode; i.e., the air conditioner was sized to run continuously on the worst day. During the worst hour of the worst day, the building load was met by the air conditioner and storage unit operating together.

Following is a summary of the results of this program, with emphasis on the storage systems:

1. Even though the test program volunteers were told ahead of time about the size of the storage units, they were "shocked" at the size when the equipment was actually delivered.

2. The loss of condensing unit capacity when the system was operated at ice storage temperatures was much greater than expected.

3. There was a high incidence of mechanical failures, especially compressors.

4. The test homes used much more electrical energy for air conditioning than comparable control homes, some of them twice as much.

The conclusion is that cold storage in the residential sector is not ready for commercialization. Most of the above problems are design-related. Areas requiring careful consideration include the advisability of retrofitting storage to existing condensing units due to the capacity derating of the condensing unit when the system is operated at lower temperatures for cool storage; the location and/or insulation of the storage tank to minimize standby losses; proper water flow to the cooling coil to adequately dehumidify, yet not exceed the design capability of the storage equipment; and indoor air flow that is matched to the characteristics of the water cooling coil.

Table 2

Summary of Residential Cold Storage Projects

Utility	TES Equipment	Number of Test Homes	Number of Control Homes	Home	Storage Location	Condensing Unit	Cooling Degree Days* Average	1980
Arkansas Power and Light Co.	A. O. Smith	29	35	Existing	Equipment room	Retrofit	1925	2579
Long Island Lighting Co.	Calmac	50	35	Existing	Outside	Retrofit	1068	1435
Pacific Gas and Electric Co.	Girton	30	30	Existing	Outside	Retrofit	1671	2018
Virginia Electric and Power Co.	Carrier/Girton	29	40	New	Equipment room	New	1353	1729
Wisconsin Electric Power Co.	A. O. Smith	70**	25	Existing	Basement	New	450	484

*Base 18.3 C^{o} (65°F) - test location.
**35 full storage and 35 half storage.

Resistance-heated hot water storage boilers for heating buildings may be of little interest to the Army. However, there are other applications for storage boilers. There may be special situations in maintenance shops or dining facilities that make resistance-heated water either desirable or necessary.

Several manufacturers offer a standard selection of large resistance-heated hot water storage tanks [8,9]. These manufactured storage boilers are usually designed to handle some moderate pressure (e.g., 50 psig) to increase the water temperature and thus storage capacity. They can be purchased with dual heaters (resistance and gas or oil) so that the heating mode may be selected at the time of charging. Standard units are available with storage capacities of up to 20,000,000 Btu with water at 280°F, which is about 15,000 gal. Higher storage requirements are usually met with multiple installations. Small storage boilers specifically designed for residential applications are also available.

Refractory Brick Storage Heaters. Electric load management has been used by utilities in Europe and England for more than 25 years [14,15]. The utilities developed an economic incentive for customers by charging lower prices for electricity purchased during off-peak periods (night) than for electricity purchased during peak periods (day). The difference in cost was great enough that storage heaters were economically attractive compared to conventional resistance heat. In the residential sector, the main thermal storage device for this purpose is the refractory brick heater (Figure 6). Today, use of these heaters in Europe is commonplace. In 1973, the total installed storage capacity in England and Germany was about 20,000 MW each. At least one European utility is now night peaking because of installed storage.

In the United States, utilities are only now developing off-peak rates for the residential sector. The Vermont Public Service Board was one of the first to approve sufficiently low off-peak rates to make resistance heat storage economically attractive. As a result, a small but viable business activity is developing to manufacture and sell refractory brick storage heaters. Several storage units available today are manufactured in Europe and shipped to the United States [16,17,18], while others are manufactured in the United States [19,20].

The storage material in the heaters is either magnesite or olivine refractory bricks. During the charge cycle, the bricks are heated with resistance heaters to 1300° to 1500°F. Controls are available that sense outdoor temperature; during moderate weather (spring and fall), they charge the system to a reduced temperature and thus prevent overheating of the living space. During discharge, hot air from the brick region is moderated with unheated room air to maintain the delivery air at a temperature of 125° to 140°F. Some storage heaters (Figure 6) are designed to heat a single room. As such, they are compact and fit nicely under a window. They are stylish and come in a wide variety of shapes (low-boys and hi-boys) and surface finishes. The maximum surface temperature is typically about 150°F, so they radiate some heat even when the blower is not on. Heater size is usually specified in terms of its power rating (in kW), and units are available in 2-, 3-, 4-, 5-, and 6-kW sizes. The heaters are usually sized to charge the unit in 8 hr, so a 5-kW unit stores 40 kWh of heat. A temperature sensor turns the power off at full charge. The heaters require 240 V to operate.

Much larger refractory brick storage heaters are available [16,20] for residential central heating systems and also for small commercial and industrial applications. Their operating principles are essentially the same as room heaters except that they are larger and equipped to attach to ductwork. Units are available with storage capacities of up to 200 kWh. They are quite heavy, and the largest unit must be installed on a floor that can

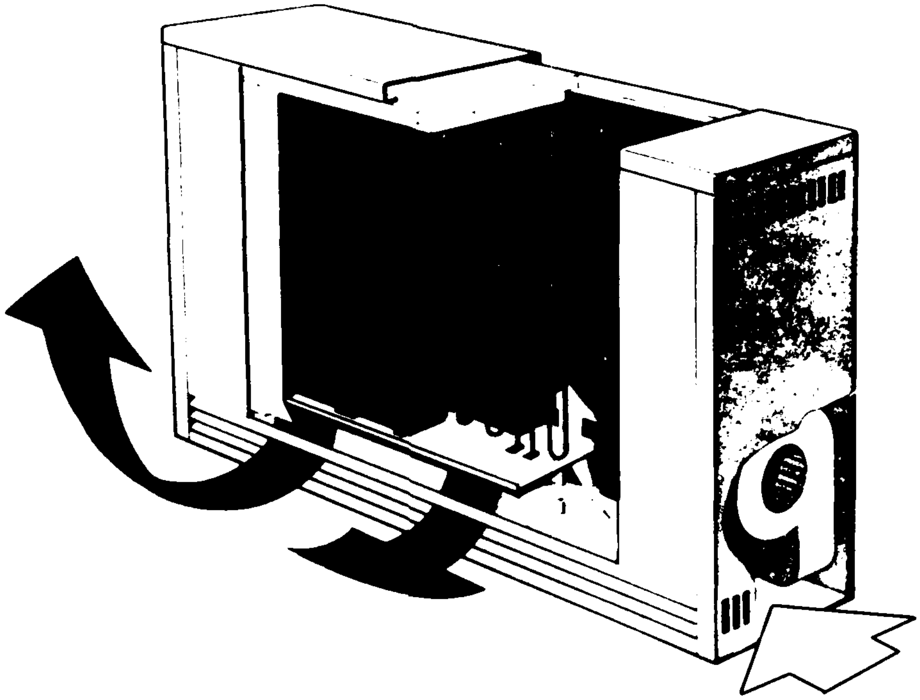

Figure 6. Room-sized refractory brick storage heater.

withstand a loading of at least 375 lb/sq ft. The largest residential central heating unit, when operating with 240-V, single-phase current, can draw almost 190 A when it is charging the storage unit and heating the house simultaneously. Thus, it is likely that a higher-capacity electric service would be required to retrofit a residence with one of these units.

The use of heat storage systems for utility electric load management was evaluated in two Department of Energy field test programs. The first is the same program referred to in the previous section on water and ice storage. Five utilities participated in this program and evaluated several types of sensible heat storage systems. Three utilities used central refractory brick storage heaters; no room sized heaters were involved. A total of 77 refractory brick storage heaters from two different suppliers were involved. Sixty-nine were installed in homes, and eight were installed in multioccupant buildings at a correctional facility. All the storage heaters were classified as commercially available at the time of the test. Most data were collected during the 1980-1981 heating season.

The following summarizes the results of these tests with emphasis on the refractory brick storage heaters:

1. There were several installation problems, which were generally related to the extreme weight and size of the storage units and the relative inexperience of the installation crews.

2. The installation costs were high. They were approximately equal to the cost of the basic storage unit, although there was considerable variation among utilities. This probably reflects the experimental nature of the program.

3. There was considerable mechanical failure at startup. However, the storage heaters were debugged and became fully operational.

4. Customer acceptance by at least one of the utilities was high, and most of the participants purchased the storage equipment at the end of the test. This utility currently has an active program to commercialize thermal energy storage in its service area.

The second Department of Energy field test involved only heat storage [21]. Forty-five homes and apartments in Maine and Vermont were equipped with heat storage units. Thirty-two homes and apartments served as controls. Although several types of heat storage units were involved, the emphasis was on dispersed ceramic heaters (room-sized), and 38 residences were so equipped. All storage heaters were commercially available. Each residence was instrumented to record inside and outside temperature, storage unit demand, and total house demand. Data were taken during the 1978-1979 and 1979-1980 heating seasons. Figure 7 shows load shifting and building internal temperature at one site during a cold week in Vermont.

The objectives of the study were to (1) determine the technical performance of storage heaters in the field, (2) assess the benefits and costs of storage to the user, utility, and society, (3) determine user acceptance, and (4) identify storage problem areas and research and development needs. The principal thrust of this field test was on the use of heat storage for load shifting from the point of view of the customer, rather than the utility. Thus, emphasis was on considerations such as human comfort and customer cost-effectiveness.

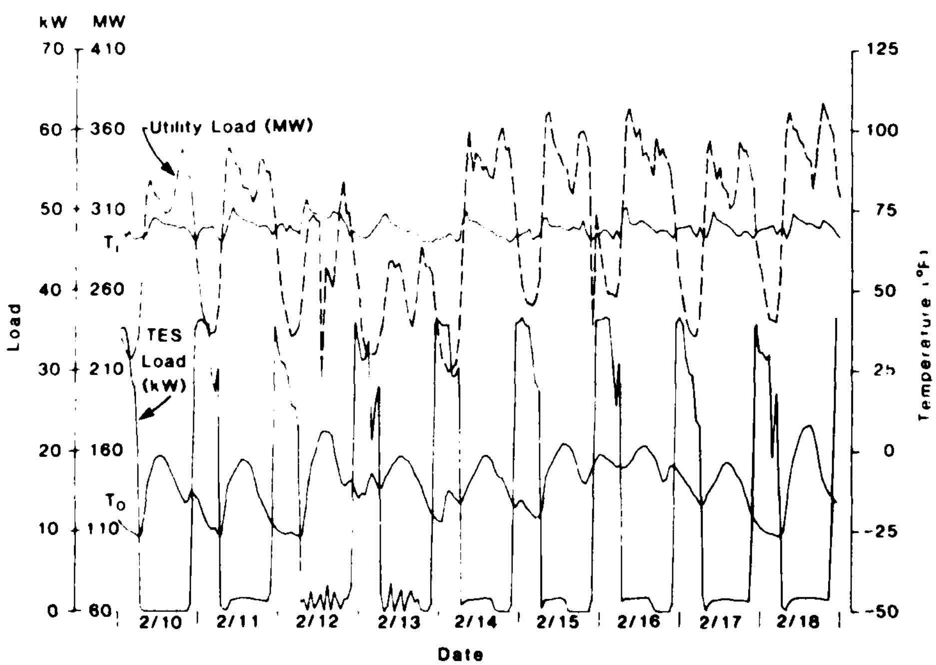

Figure 7. Performance of dispersed thermal storage system.

The test produced the following results:

1. There were very few installation problems or problems associated with defective parts. This is probably because the test units were installed by contractors that have historically worked with the storage unit vendors.

2. Statistical comparison of the residences with storage to these without storage showed no significant difference in annual electrical use.

3. From the point of view of human comfort, acceptance of the storage units was high, and most participants said that they would "recommend it to a friend or neighbor."

4. The average installed cost of a dispersed refractory brick storage system for this test was $3.64/sq ft. Installed cost of an electric baseboard heating system was $1.69/sq ft. Thus, the electric heating system, with storage, costs about 2.2 times as much as a conventional electric heating system.

The refractory brick core of a storage heater represents a substantial part of the total heater cost. Recent research in the United States toward developing a chemically bonded olivine for storage heaters [22,23] has been rather successful. Chemical bonding would eliminate the firing step in the manufacture of refractory bricks and thus significantly affect their cost.

Concrete Heat Storage. The principal commercially available heat storage application where concrete is the storage medium is subfloor heaters [24] (Figure 8). The resistance heaters are energized when off-peak rates are in effect or when the post electrical demand is low. The sand and concrete floor are then heated to some predetermined temperature. The floor then releases heat slowly and remains warm during the subsequent period of peak rates or high demand. Although some heat is lost to the earth, the manufacturer claims that it is a small amount. Because of the uncontrolled nature of the energy release, the temperature of the heated space cannot be controlled precisely. Thus, the concept is not suitable for office buildings and living facilities, but rather for storage and maintenance facilities. In addition, the concept is primarily of interest for new construction but not retrofit applications. The manufacturer claims that the installation cost of such a heating system is usually less than $0.50/sq ft.

A subfloor heating system of this type has certain characteristics that may be of special interest to the military because their requirements are often quite unique. For example, because of the massive energy storage system, a building with a subfloor heater may remain at a tolerable temperature for much longer than a conventionally heated building during a power outage. Also, since the electric heating system can be installed totally external to the buildup envelope, it may be ideal for spaces prone to heating explosion.

Heat Transfer Oils and Salts. In the United States, the industrial sector has commonly used heat transfer oils and salts for many years. Their physical properties and characteristics are well known [54,55,56,57,58]. The solar thermal power program uses these materials for high-temperature sensible heat storage. The Barstow demonstration project (10 MW) storage system contains 240,000 gal of Caloria HT-83 oil. Since these oils are rather expensive, the storage tank contains sand and rocks to assist in storage. In its fully charged state, the storage system is at 575°F.

A nitrate salt storage system has been tested at the Central Receiving Test Facility in Albuquerque, NM. The storage system is a two-tank arrangement, with one hot

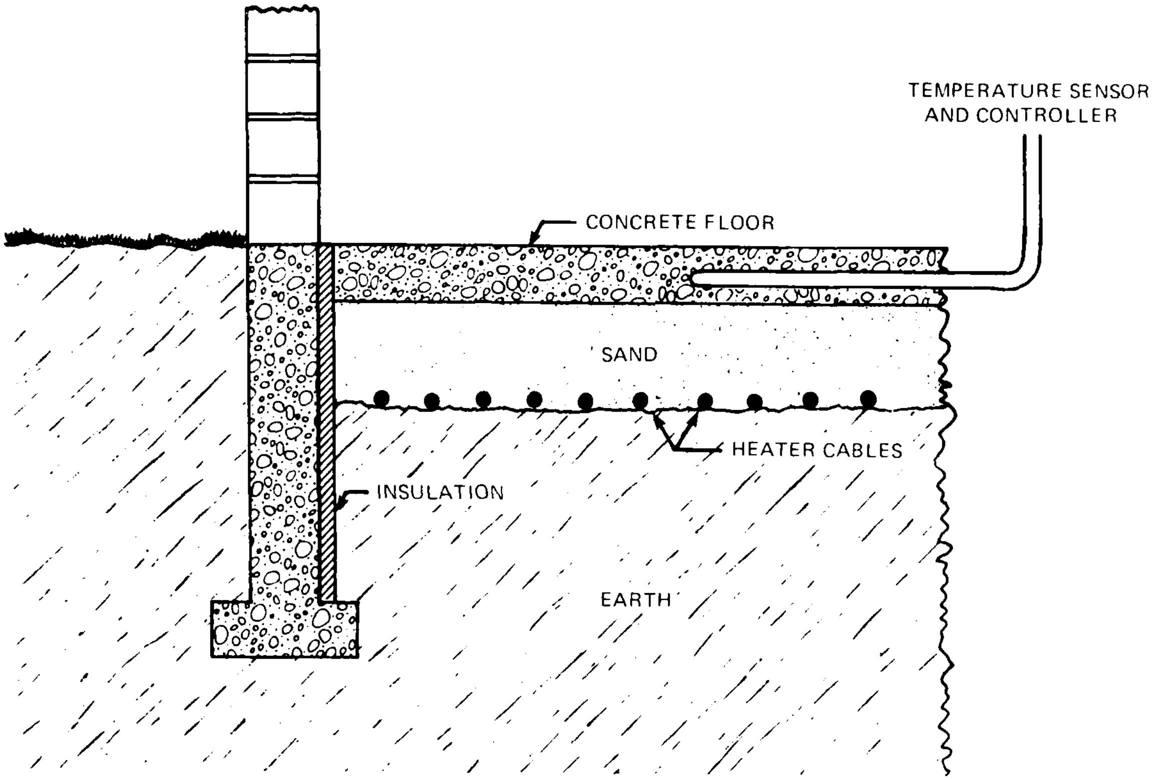

Figure 8. Subfloor heater with concrete and sand storage.

tank and one warm tank. The salt is cycled between 1050°F and 550°F. Heat transfer salts and oils are appropriate only for storage at very high temperatures.

Nonaqueous Latent Heat and Cold Storage

Thermal energy storage (TES) systems can be classified into two generic types: sensible and latent. Sensible heat storage involves raising the temperature of a substance; the amount of thermal energy stored is directly proportional to the temperature rise. On the other hand, the quantity of thermal energy stored as latent heat is not a direct function of the material temperature rise, but rises dramatically at the phase change temperature, T_c, as shown in Figure 9. Latent TES materials provide large usable thermal storage capacities over small operating temperature ranges, if this temperature range spans T_c. In thermal storage applications, where storage mass or volume is constrained, or where storage at a specific temperature is required, sensible heat storage techniques are often not effective. However, latent heat storage might be usable in such situations. Latent heat storage involves a physical or chemical change of state in a substance, accompanied by the absorption or emission of heat. Freezing, melting, condensation, vaporization, and many chemical changes are examples of latent heat processes. The general class of substances that exhibit this behavior are termed phase change materials (PCM). The most common latent heat processes are heats of solution, heats of sorption, solid-solid transitions, and fusion or liquid-solid transitions.

Strictly speaking, the use of ice as a cold storage medium is a form of latent storage. However, it differs from the more advanced materials discussed in this section

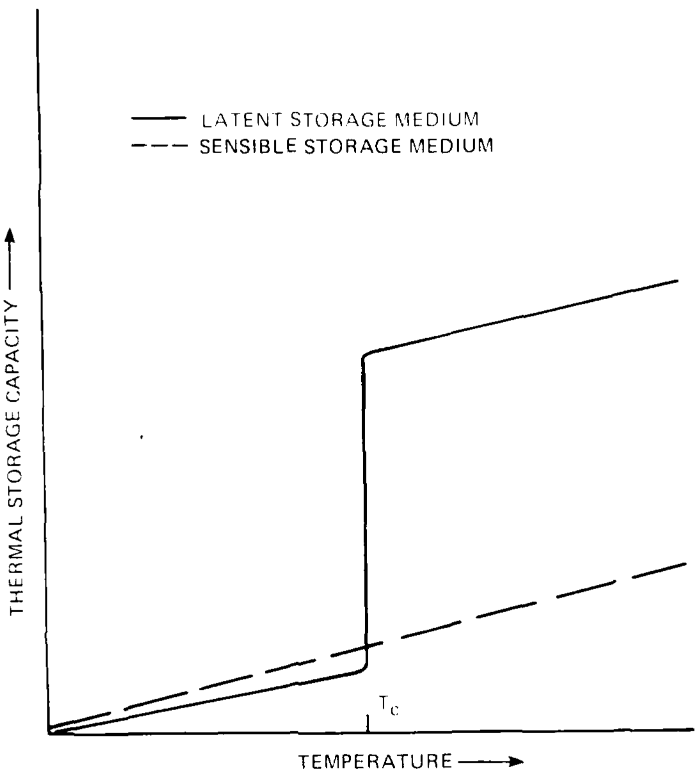

Figure 9. Comparison of thermal capacities of sensible and latent heat storage media.

in that it is a well-established cold storage technology and is readily available. Ice is also the main competition to cold water storage for electric load management. Thus, ice storage was discussed in the section *Sensible Heat and Cold Storage (Including Ice).*

Heat of Solution. An energy change accompanying the dissolution of a substance is termed its heat of solution. The heat of solution process is easiest explained in terms of the mixing of two liquids. When two nonideal liquids are mixed, heat is absorbed or released. Such binary compositions are completely miscible above a critical solution temperature and are only partially miscible below this temperature. The partial miscibility produces two distinct liquid phases having characteristically higher and lower concentrations of a given liquid species. Candidate binaries include (1) glycols and polyhedric alcohols that are mixed with water and (2) certain alkane-alcohol combinations. Since use of binary liquids as TES media requires a miscibility change over a temperature range, the behavior of such a system more closely approximates that of a sensible heat storage system with an enhanced specific heat rather than a latent heat system. An examination of many liquid binary systems for cooling that exhibit a heat of solution effect has identified none with a latent storage effect higher than 33 Btu/lb in the <68°F temperature range [69]. This value is much less than what is available with other latent storage processes, and no large-scale TES systems that exploit this technique have been manufactured.

Heat of Sorption. Sorption is the process whereby solid or liquid materials (sorbents) take up and hold other substances brought into contact with them. Sorbed substances are usually gaseous, with water vapor most frequently used as the sorbed

compound. The sorption process generates heat mainly through the condensation of water vapor. The weight of water vapor held by a sorbent can change in response to the difference between the partial pressure of water vapor in the surrounding atmosphere and the vapor pressure of the water held by the sorbent. Although all materials are sorbents to some degree, the term is usually reserved for materials that have a large capacity for moisture.

Absorbents are compounds that change physically and/or chemically during the sorption process. Solid absorbents include salts like lithium chloride (LiCl), which upon absorbing water is converted into a hydrate ($LiCl{\cdot}5H_2O$), and sodium sulfide (Na_2S), which also forms a hydrate and is currently being used experimentally in the Swedish Tepidus System [70]. In both cases, the reduced vapor pressure resulting from the hygroscopic nature of the absorbents is used to drive water vapor from one location to another. This principal feature of solid absorbents facilitates their use in chemical heat pump systems, in which thermal energy contained in water vapor is transferred from a lower to a higher temperature and combined with the solid absorbent. Liquid absorbents include sulfuric acid, the alkene glycols, and solutions of halogenated compounds. Chemical heat pump systems based on these materials are generally in the research stage; however, continued development on these systems can be justified due to the concept's simplicity and flexibility as a storage/heating/cooling device.

Materials that do not change physically or chemically during the sorption process are termed adsorbents. Solid materials including silica gel, natural or synthesized alumina silicates (Zeolites), and activated bauxites have porous structures of microscopic dimensions that produce an extensive external surface area where adsorption can occur. The amount of material adsorbed under equilibrium conditions is proportional to the surface area of the desiccant, if access to the interior is available. Water vapor in air is the most common component used with adsorbents. In this process, moisture is driven into the porous structure through a vapor pressure difference. The process is completely reversible and in most cases is done by appling heat to drive off the moisture, thereby regenerating the desiccant. In desiccant cooling systems for buildings, supply air is first dried with a desiccant bed, thereby warming the air, then cooled by heat exchange, and finally humidified by passing it through an adiabatic humidifier. Further development of this concept is needed [71].

Solid-Solid Transitions. Many materials undergo reversible phase changes in the solid state during which they absorb or release energy. During the cooling process, the solid structure changes from one of high symmetry, in which materials are orientationally disordered, to a rigid lattice, in which the molecules are more restricted in orientation. Common materials, such as paraffin, undergo solid-solid transitions near their melting temperatures. These transitions can be more energetic than the theoretical heat of fusion itself. It is possible to combine two or more materials, each capable of solid-solid transitions, to form a solid solution that has a lower phase-change temperature than that of any of the constituents. Solid solutions can form only when the molecules or atoms of the constituents are similar in size and state. Research is under way to develop a solid-solid transition material that would change phases at ~86°F [72]. This material is based on compositions of the homologous compounds pentraerythritol, pentaglycerine, and neopentyl glycol, and is intended for use as thermal storage in passive solar architecture. In a broad interpretation of the solid-solid transition, long-chain hydrocarbons can be crosslinked to such an extent that upon melting, the polymer does not liquify, but retains its shape [73]. This technique has been developed for pellets of polyethylene and has resulted in a form-stable pelletized material that changes phase at T_c = 266°F with a latent heat of fusion of 72 Btu/lb. It has been suggested that these pellets would be an appropriate storage medium for exhaust heat from a diesel engine.

Heat of Fusion. The melting and freezing of a substance constitutes an energetic process associated with the liquid/solid phase change. The most common liquid/solid phase change is found in water, wherein 144 Btu/lb of thermal energy is released or absorbed at the phase change temperature of 32°F. This heat of fusion is large, and is usually considered to be the benchmark for comparison with the latent heat of other liquid/solid PCMs. Other single-component materials that freeze or melt at higher temperatures are paraffins. These are hydrocarbons that contain alkanes (C_nH_{2n+2}) as major constituents and, depending on the molecular weight, have melting points between 43° and 175°F, and heats of fusion from 43 to 108 Btu/lb. There are also multicomponent materials such as hydrated salts which melt into a liquid solution from a solid crystalline form. The freeze/melt behavior of such materials is often complicated because more than one solid phase can be formed. Nevertheless, such materials are relatively inexpensive, possess relatively high heats of fusion, and are available over a range of T_c of interest; thus, they are the basis for the PCM/TES systems currently on the market.

Phase Change Storage Media. Because of their small-volume changes during the phase change, compact thermal storage, and reduced container requirements, liquid/solid PCMs have an advantage over other forms of phase change, and many materials have been identified as attractive TES media. As single-component media, hydrocarbons such as waxes and paraffins initially seem attractive; however, they have the disadvantages of comparatively high costs, flammability, low thermal conductivities, and low densities. In the moderate temperature range of interest (40° to 250°F) for heating and cooling building's inorganic salt hydrates are the best PCMs, combining low costs, high latent heats of fusion, good thermal conductivities, low toxicity, and low flammability characteristics. These materials are solid crystals of inorganic salts that have a specific number of water molecules bound to each molecule of anhydrous compound. These compounds have the general formula $S \cdot nH_2O$, where S represents a molecule of the anhydrous salt and n is the number of water molecules. At the phase change temperature, T_c, the salt hydrate "melts" and the anhydrous salt dissolves partially or completely in its water of hydration. Often, the anhydrous salt is not completely soluble in its water of hydration, leading to precipitation or formation of hydrates with lower heats of melting. This behavior is termed incongruent melting and is a characteristic of many salt hydrates which otherwise would be very promising as TES media. Efforts to arrest this irreversible process have used thickeners, such as clays and gels, with varying degrees of success to prevent precipitation of the anhydrous salt. By focusing on congruent and semicongruent compounds that exhibit only small deviations from the ideal, Dow Chemical has developed and is presently marketing thermal storage materials in the temperature range for building heating and other applications. Other hydrated salts that have been used for TES are available from many suppliers of inorganic chemicals. Table 3 lists commercially available latent TES materials, characteristics, 1982 costs, and suppliers. Although there are many additional hydrated salts that melt in temperature ranges of interest, those listed in Table 3 are being marketed as thermal energy storage compounds.

Phase Change Material Systems. A recent survey [74] has identified three PCM systems that use bulk storage of the PCM with internal heat exchange, and many more which have relatively small individual PCM containers that require heat exchange on the container exterior. Calmac Corporation has developed a "Heat Bank" TES system that uses bulk containment of PCMs in unpressurized, plastic cylindrical tanks with an internal plastic tube heat exchanger. Originally developed for solar applications, this system (Figure 10) uses $Na_2S_2O_3 \cdot 5H_2O$ with a melting point of 117°F and a small stirrer to promote nucleation throughout the PCM and to prevent phase separation. Although several tank geometries have been designed, the typical tank size is 4.0 ft in diameter and 4.0 ft high, and contains 314,000 Btu of latent heat storage and 380,000 Btu total storage capacity when the sensible heat contribution is included over a 35°F storage

Table 3

Thermal Storage Compounds Commercially Available

Name	Manufacturer	T_c (^oF)	Heat of Fusion (Btu/lb)	Specific Gravity	Cost (¢/lb)
TESC-81 (based on $CaCl_2 \cdot 6H_2O$)	Dow Chemical	81	82	1.71 (s) 1.53 (l)	9
TESC-135 (based on Mg salts)	Dow Chemical	135	58	1.60 (s) 1.52 (l)	25
TESC-190 (based on Mg salts)	Dow Chemical	190	70	1.64 (s) 1.55 (l)	25
TESC-240 (based on $MgCl_2$)	Dow Chemical	240	72	1.57 (s) 1.45 (l)	11
E-400 (based on polyethylene glycol)	Dow Chemical	46	43	1.12	60
E-600 (based on polyethylene glycol)	Dow Chemical	72	54	1.13	60
$Na_2S_2O_3 \cdot 5H_2O$ (photograde quality)	Allied Chemical	120	90	1.7	24
$Na_2S_2O_3 \cdot 5H_2O$ (98% purge liquor)	Allied Chemical	117	88	1.7	15

operating temperature range. When fully charged, total thermal loss from the unit on standby is less than 5 percent per day. Total cost (not including installation) is \$3200, equivalent to \$8410/MBtu.

Thermal Energy Storage, Inc. (TESI) is marketing a TES device similar to the Calmac system. The internal heat exchanger shown in Figure 11 consists of double-tube

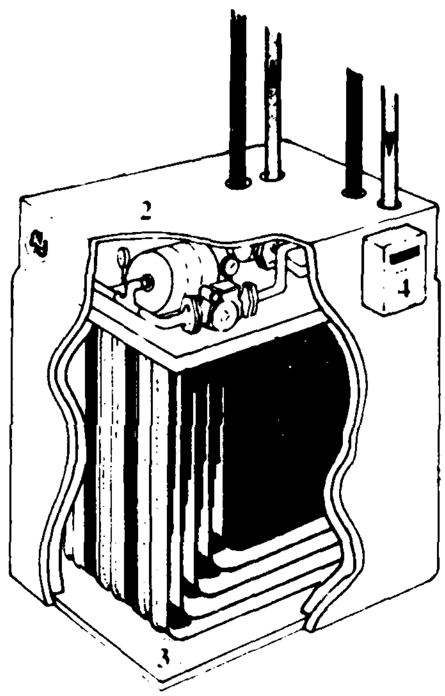

Figure 10. Calmac heat bank.

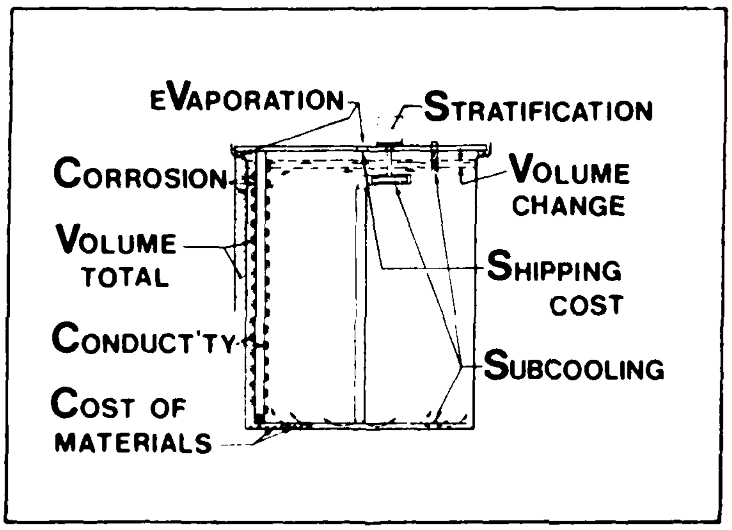

Figure 11. TESI Model ST-260 storage unit with $Na_2SO_4 \cdot 5H_2O$ as storage medium.

finned aluminum wound in flat layers with interconnections above the PCM surface. The PCM used is photograde $Na_2S_2O_3 \cdot 5H_2O$ with additives to limit crystal size and allow supercooling to room temperature to facilitate on-site filling. A cold finger plus stirrer is used to promote nucleation of the PCM at T_c during system operation. The basic unit being sold is model ST-260 with a total storage capacity (latent and sensible) of 253,000 Btu over a 40°F operating temperature. The tank contains 2650 lb of salt for a total system weight of 3650 lb. Installation of the system has been simplified by design of a "Hot Pac" system which resides on top of the storage tank and contains all of the valves, the expansion tank, and the small pump needed to operate the system in an active solar application. The total unit price (uninstalled) is \$3500, equivalent to \$14,000/MBtu.

The "Heat Battery" manufactured by O.E.M, Inc. (Figure 12) is being marketed in a variety of sizes and employs a unique approach to heat transfer to and from the contained PCM ($Na_2SO_4 \cdot 10\ H_2O$). The PCM is agitated by a light, water-immiscible oil which is injected through a diffuser; it then rises through the PCM, removing or depositing heat, and enters a floating oil layer above the PCM for recirculation through the salt. The diffuser shown in Figure 12 is used to inject the oil at tank levels controlled by

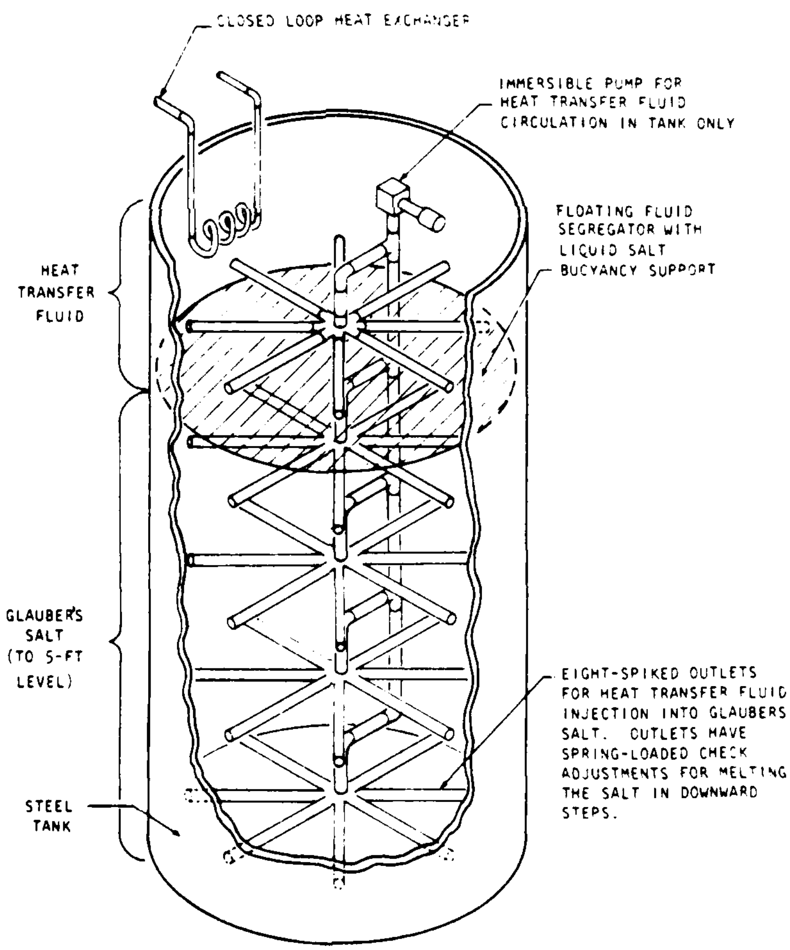

Figure 12. OEM heat battery.

oil pressure; the cooled oil flows from the lowest nozzle array first, and freezes the PCM from the bottom up. For melting, the lower nozzles are blocked by solid PCM and the oil flows out of the uppermost nozzles first melting the salt from the top down. Since there is no internal coil heat exchanger in the O.E.M system, capacity is mainly a function of available tank size. A range of sizes is available: Model 3879 contains 358,000 Btu and costs (not installed) $3846, while at the upper end of TES sizes, Model 123122 contains 5,904,000 Btu and costs $28,812.

Many small, low-weight PCM "modules" have also been developed primarily for solar applications (Table 4). These are simply containerized PCMs in which heat transfer occurs through the container surface to freeze and melt the PCM.

Although a number of thermal storage systems with PCM storage media are available commercially, they have been on the market for only a few years. In general, their long-term stability has not yet been demonstrated.

Mechanical Energy Storage Systems

Mechanical energy storage is defined as a storage technology that uses a mechanical driver to convert primary energy to another form for storage. In the context of energy storage appliations for the Army, the primary energy source would probably be electricity. For utilities, the primary energy source may include high-pressure steam. The most common mechanical energy storage technologies include pumped hydroelectric, compressed air, and flywheels.

Compressed Air Energy Storage

Compressed air energy storage (CAES) [25] is a being developed specifcally for use by the electric utilities to level out their generation load profiles. Using CAES, a utility will be able to store cheaper energy, generated by the base load plants during periods of low demand, for subsequent use during periods of high demand. By its nature, the CAES concept is directed toward large installations. Thus, it may be considered as an appropriate storage concept for a large Army post, but not for a single building. At a large Army post, electric requirements are high, there is a considerable diurnal cycle demand, and peak electricity costs more than off-peak electricity because of time-of-use rates, demand rates, or both.

Figure 13 shows a conventional CAES cycle. During the charging phase of the cycle, an electric motor drives a compressor train and compresses air to between 600 and 1100 psi for storage in the air storage reservoir. The heat at compression is rejected to the atmosphere. During the discharge phase, compressed air is released from the reservoir, heated using petroleum fuels, and used to drive the turbine/generator. Exhaust gas from the low-pressure turbine may be used to preheat inlet air to the high-pressure turbine. Storage reservoirs may be operated in either the constant volume (uncompensated) or constant pressure (compensated) mode. In the constant pressure mode, the storage system volume is variable and is compensated for by a column of water.

Underground storage is used because of the large column of air that must be cycled. For example, if air is stored at 1000 psi, then the storage volume required to generate 1000 MW for 10 hr (10,000 MWh) is about 900,000 cu yd. Three storage reservoirs are usually considered: confined aquifers, solution mined-salt cavities, and excavated hard rock caverns. Siting constraints include the availability of suitable underground formations.

Table 4

Thermal Energy Storage Modules Using Phase Change Materials

Manufacturer	Product Name	Phase Change Material	Container	Total Weight (lb)	Phase Change Temperature	Heat Storage Capacity (at phase change temperature)
Architectural Research Corp. 40 Water St. New York, NY 10004 (212) 943-3160	Sol-Ar-Tile	Glauber's salt mixture	Polymer concrete tile, 2 ft by 2 ft	44	73°F	800 Btu
Blue Lakes Engineering Pace Corp. P.O. Box 1033 Appleton, WI 54912 (414) 733-0941	Thermo 1-81	Calicum chlor-ide hexahydrate	Black polyethylene tube, 6 ft long, 3 1/2-in. diameter	35	81°F	2460 Btu
Boardman Energy Systems, Inc. 5720 Kennett Pike P.O. Box 4198 Wilmington, DE 19807 (212) 388-7454	Boardman tube	Glauber's salt mixtures	Plated steel tubes, 30 in. long and 4-in. diam. built-in spacers, selective coating available	22	45°, 64° 74°, 78° 81°, 89°	1444-2000 Btu, varies with phase change temperature
Energy Materials, Inc. 2622 South Zuni Englewood, CO 80110	Thermalrod-27	Calcium chlor-ide hexahydrate	Black polyethylene pipe, 6 ft long, 3 1/2-in. diam.	35	81°F	2542 Btu
Kal Wall C...poration Solar Components Division 88 Pine Street P.O. Box 237 Manchester, NH 03105 (603) 688-8186	Thermal storage pod	Calcium chlor-ide hexahydrate	Fiberglass rein-forced polymer container, 48 by 16 by 2 in. or 24 by 16 by 2 in.	29 or 14.5	81°	2130 Btu
PSI Energy Systems, Inc. 1533 Fenpark Drive St. Louis, MO 63026 (under OEM agreement with Dow Chemical Company)	Thermol-81	Calcium chlor-ide hexahydrate	Black polyethylene tube, 6 ft long, 3 1/2-in. diam.	35	81°F	2460 Btu
Texxor Corporation 9910 North 48th Street Omaha, NE 68152 (402) 453-7558	Texxor heat cell	Calcium chlor-ide hexahydrate	Steel cylinder, 7 in. long, 4.26-in. diam.	4.56	81°F	345 Btu
DOW Chemical Co. Midland, Michigan	Enerphase TES panel	TESC-81 (cal-cium chloride hexahydrate)	Ribbed rectangular container 14 in. x 22 in. x 2.2 in.	23	81°F	1800 Btu between 65 and 90°F

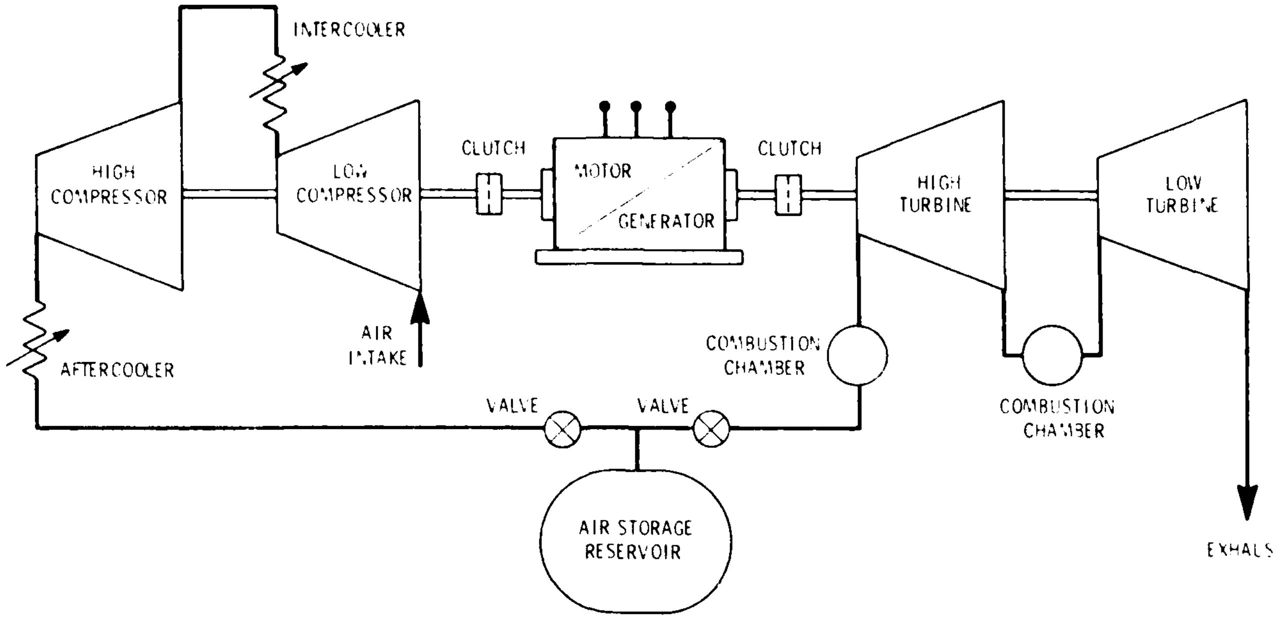

Figure 13. Conventional compressed air energy storage cycle.

The Department of Energy conducted three parallel design, siting, and cost studies, each based on one of the three reservoir types. Potomac Electric Power Co. (PEPCO) conducted the hard rock feasibility study, Middle South Services (MSS) the salt cavity study, and the Public Service Company of Indiana (PSI) the aquifer study.

PEPCO selected a site northwest of Washington, D.C., in Maryland as their prime candidate. The storage chamber was to be located in Sykesville gneiss underlying the site. Several boreholes were drilled, one to a depth of 2556 ft, to determine the suitability and characteristics of the rock. After examining 47 sites, MSS selected the Carmichael salt dome near Jackson, MS, as their candidate site. PSI identified 14 potential aquifer sites (10 in Illinois and four in Indiana). Using a ranking and evaluation process they eliminated seven sites.

Each utility then retained an architect/engineer to design and cost a CAES facility. Table 5 provides system specifications and estimates of their performance. In general, the performance of the three systems, as characterized by the Fuel Heat Rate and the Electric Energy Ratio, is comparable. Table 6 shows the estimated capital cost of each facility. (Care must be taken in comparing these costs as tabulated, because the basis for the estimate is not the same in each case. The power level and storage capacity (hours) are different for these systems. Also, the methods of including contingency costs vary greatly.) When the cost results in Table 6 are normalized to a consistent set of system specifications and assumptions, the following conclusions are drawn:

1. Aquifer and salt dome storage facilities cost roughly 60 to 70 percent of the equivalent hard rock cavern.

2. In this comparison, aquifer storage facilities were somewhat less expensive than the salt cavity, but this difference could easily be reversed with different salt dome and/or aquifer characteristics.

3. The major difference between the total plant cost estimates lies not in the cost of the storage facilities, but rather in the vendor estimates for turbo machinery costs.

Table 5

CAES System Specifications and Performance

	PEPCO (Hard Rock)	MSS (Salt)	PSI (Aquifer)
Power (MWe)	924	220	1120
Storage capacity (hours)	10	8	10
Fuel heat rate (Btu/kWh)	4250	3980	4090
Electric energy ratio (kWh in/kWh out)	0.75	0.77	0.70

Table 6

Estimated Capital Cost of CAES Facilities ($/kW)

	PEPCO (Hard Rock)		MSS (Salt)		PSI (Aquifer)	
Storage system	61	16%	43	13%	49	14%
Turbomachinery	186	50%	218	67%	158	45%
Balance of plant	129	34%	64	20%	147	41%
Direct cost	376	100%	325	100%	354	100%
Indirect of contingencies	112		72		36	
Total cost	488		397		390	
Date of dollars	July 1979		July 1979		April 1981	

The CAES concept can be considered technically proven, since a 290-MW CAES plant is currently operating in Huntorf, West Germany. This plant was ordered in 1973 and commissioned in 1978. Aside from some initial startup problems, the plant has been operating successfully. Underground caverns dissolution-mined in salt domes are used for storage. The design charge cycle is 16 hr long, and the motor draws 60 MW. The design discharge cycle is 4 hr long, with the plant generating 290 MW. The total cost of the plant was estimated to be about 70,000,000 U.S. dollars or $240/kW.

One U.S. utility (Soyland Power Cooperative, Inc.) had signed contracts to design and build a 220-MW CAES facility in Illinois. It was planned to use a hard rock, compensated storage cavern. However, early in 1983, the utility announced that construction at this facility would be "indefinitely deferred" due to changing market conditions. Relative overcapacity by regional utilities resulted in long-term power purchase agreements which were not available a few months before.

The Department of Energy and the Electric Power Research Institute (EPRI) have heavily supported the CAES concept. DOE's two major goals were to:

1. Determine long-term reservoir stability criteria for CAES operating conditions

2. Identify, determine the feasibility of, and develop second-generation CAES concepts that minimize the need for, or do not require, petroleum fuels for firing CAES plant turbines.

A Battelle publication summarizes reservoir stability criteria and research directed toward minimizing or eliminating petroleum fuels [25]. Of the many efforts under way, the system closest to technological readiness and most economical is the adiabatic CAES. In this system, the heat rejected during compression is stored for subsequent use as a replacement for petroleum fuels during generation. Storage is underground in high-pressure caverns. The selected storage medium is a packed bed of sintered iron oxide pellets. To prevent thermal-induced deterioration, the cavern walls must be insulated from the pebble bed, which may reach temperatures of up to 870°F.

Flywheel Energy Storage

Kinetic energy stored in a flywheel is a relatively old technology. Its earliest known application was the potter's wheel. A more recent example is the modern automobile. The internal combustion engine operates smoothly because a flywheel incorporated in the drivetrain stores the energy that is supplied intermittently by explosions in the cylinders [79]. The action of the flywheel thus smooths out the variable power inputs.

The basic principle of flywheel energy storage is that a rotating wheel represents stored mechanical, or kinetic, energy. The amount of energy stored depends on the inertia of the wheel and its rotational speed. Energy is added by increasing the wheel speed and withdrawn when the wheel is slowed down, typically by coupling it to a load.

Use of the flywheel as a major storage system has been very limited. The Oerliken Electrogyro Bus, which began operating in the early 1950s in Switzerland [80], is an early example of an operating flywheel system. Electricity was used to spin-up the metallic flywheel at the bus stops. The flywheel was then used to power the bus. The average distance between recharges was 0.75 mi. Although technical operation of the system was satisfactory, there were major objections from passengers who had to endure relatively long waits during the recharging stops.

In 1976, New York City's Metropolitan Transit Authority satisfactorily operated two prototype subway cars that used flywheel/electric propulsion systems. The flywheels were used in a regenerative braking mode with the energy recovered during braking stored in the flywheel. Energy discharged from the flywheel was used to accelerate the cars. In 6 months of operation, the flywheel subway cars showed a net energy savings of 33 percent over conventional cars [81].

Flywheel systems have several characteristics that make them attractive for energy storage applications. There is considerable latitude in the power transfer system. The flywheel can be charged or discharged mechanically or inductively. Thus, the input/output equipment can be tailored to suit the application. Flywheels will likely have a long service lifetime (about 20 to 30 years), with low maintenance requirements. Also, the storage density and lifetime of the flywheel is relatively insensitive to charging and discharging rates. This makes flywheels attractive for applications where a slow charge/rapid discharge (or vice versa) duty cycle is desired.

At present, flywheels are not commercially available as a storage technology, although systems can be engineered for specific applications using metallic flywheels. Recent efforts have focused on developing composite flywheels because of their potential for higher energy storage densities and more benign failure modes.

Technology Description. A flywheel energy storage system has several subsystems: the rotor, containment housing, vacuum system, rotor suspension, and power input/output system. The latter three are generally commercially available.

The rotor must be run in a vacuum to reduce frictional air drag. When a composite material rotor (e.g., graphite/epoxy) is used, frictional heating of the wheel can significantly reduce the expoxy's strength. Thus, a "harder" vacuum is required than for a metallic flywheel.

The suspension system consists of lubricated bearings of standard design. Input/output interfacial equipment can be either mechanical or electrical. In mechanically coupled systems, power transfer uses clutches and a transmission; electrically coupled systems use a motor/generator.

Recent advances in flywheel technology have focused on the rotor and containment housing. Limitations on ultimate strength produce maximum energy densities of about 50 Wh/kg for metallic rotors (Figure 14). In actual use, this energy density is greatly reduced. First, the maximum speed of the wheels will be lower than the ultimate to maintain a safety factor. Second, practical transmission considerations result in a ratio of high-to-low speed of somewhere around 2:1 (this 50 percent speed depth of discharge [DOD] corresponds to a 75 percent energy DOD). These two factors result in the operational storage density being about half the ultimate value. For metallic flywheels, this value is about 25 Wh/kg. The flywheel system storage density is further reduced by the weight of the containment housing. For metallic flywheels, containment requires thick walls and is heavy--generally about two to four times the weight of the rotor itself. Thus, the operational energy density for a metallic flywheel system is about 10 Wh/kg.

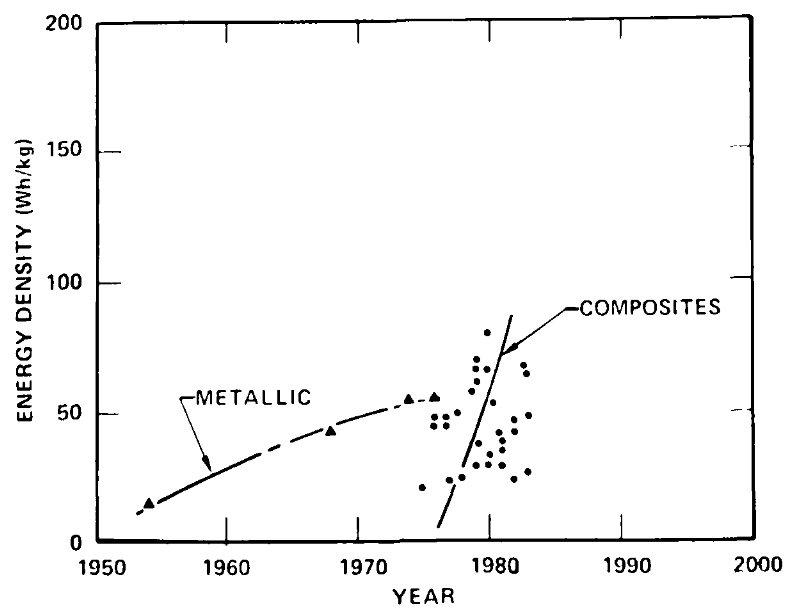

Figure 14. Progress toward increasing the energy storage density of flywheel.

In applications where weight of the storage system is not important, metallic rotors are adequate; however, in many applications, higher energy densities are required. To increase the storage density of flywheel systems, attention has focused on composite materials such as graphite/epoxy, Kevlar/epoxy, and S-glass with reasonably good success (Figure 14). These materials have several advantages. They exhibit higher specific strength (ultimate strength [σ] divided by density [ρ]). Steels typically have a σ/ρ of 50 to 70 Wh/kg, while a Kevlar/epoxy composite has a value of 340 Wh/kg. This allows higher speeds to be attained with resultant increases in storage density. When composite wheels fail, they tend to break up into small pieces of fluffy material. This makes containment requirements less severe than for metallic rotors and can lead to lighter-weight containment housings.

A number of advanced rotor designs have been fabricated and tested [82]. As shown in Table 7, a variety of wheel types and materials were used. A number of designs achieved energy storage densities exceeding 60 Wh/kg at ultimate speed. Further research concentrated on four specific designs and expanded the testing program to include cyclic fatigue tests. As shown in Table 8, disk (using SMC) and disk/ring (SMC disk graphite/epoxy ring) designs both completed 10,000 cycle tests. Subsequent ultimate energy density tests showed values of 48.6 and 63.5 Wh/kg for the disk and disk/ring rotors, respectively. Interestingly, these values are higher than those attained by similar rotors that were not cycled prior to ultimate density testing. Therefore, composite

Table 7

Results of Ultimate Storage Capacity Tests for Early Rotor Designs

Manufacturer	Wheel type	Material*	Burst energy** (Wh/kg)	σ/ρ*** (Wh/kg)
Brobeck	Rim	SG/K49	63.7	340.2+
Garrett/ AiResearch	Rim	K49/K29/SG	79.5	317.4+
Rocketdyne	Overwrap rim	G	36.1	274.2
APL-metglass	Rim	M	24.4	91.2
Hercules	Contoured pierced disk	G	37.4	274.2
AVCO	Pierced disk	SG	44.0	262.6
LLNL	Tapered disk	G	62.6	274.2
LLNL	Flat disk	SG	67.1	262.6
GE	Solid disk	SG/G	55.1	263.7++
Owens/Lord	Disk	SMC/G	27.8	95.0++
		SMC/G	36.6	115.0++
		SMC/G	25.0	62.71++
		SMC	17.5	43.8++

*Material legend is: SG = S Glass; K49 = Kevlar 49; K29 = Kevlar 29; G = Graphite; M = Metglass; SMC = S-glass sheet molding compound.

**Burst test results as reported by Department of Energy, Mechanical Energy Storage Technology Program.

***Calculated as follows: $K' = BE/(\sigma/\rho)$.

+Assumes higher σ/ρ material at outer part of rim is limiting factor.

++Proportional by weight.

Table 8

Flywheel Test Results for Advanced Rotors

	Disk	Disk/Ring	Flywheel: Subcircular Rim	Flywheel: Bidirectional Weave
Completed 10,000-cycle test	Yes	Yes	No.*	
Ultimate energy density	48.6**	63.5**	65.7	37.3

*Rotor failed at 2586 cycles.
**Rotor had previously completed cyclic test.

flywheels have currently demonstrated 10,000-cycle lifetimes and have attained energy densities 25 percent higher than metallic rotors.

Potential Applications. Flywheels have been examined for a number of applications, most notably for vehicles, electric utilities, and household photovoltaic systems. These applications are covered fairly extensively in the literature [79,83,84,85,86].

The flywheel can serve several functions in vehicular applications. By using the flywheel to accelerate the vehicle, the peak power required from the engine decreases. This allows downsizing of the engine and operation of the engine at its most efficient point. Also, braking energy can be recovered and reused for accelerating the vehicle.

Automobile applications have received the greatest amount of attention so far. Two drivetrain configurations have been proposed [85]: one for heat engine vehicles and another for electric vehicles. Figure 15 shows a heat engine/flywheel power train with components arranged in a series power flow arrangement. The heat engine and flywheel are linked by a speed reduction gear of fixed ratio, and the flywheel is linked to the wheels through a continuously variable transmission (CVT), which matches flywheel rotational speed to the road speed requirement. The flywheel subsystem here is a through-shaft configuration, reflecting technology employed in the Department of Energy ETV-2 vehicle design. In this power train arrangement, the flywheel effectively drives the vehicle, while the heat engine operates in an on-off mode to maintain flywheel speed above a controlled lower limit. When on, the engine operates at near wide-open throttle, minimum brake specific fuel consumption (BSFC) conditions for maximum efficiency. Vehicle kinetic energy during deceleration is recovered by using the forward motion of the vehicle to spin up the flywheel.

Figure 16 shows a second flywheel drivetrain. The prime propulsion unit here is a battery-powered, separately excited direct current motor mechanically linked to the vehicle wheels through a two- or three-speed transmission. The flywheel unit outputs electric energy to augment the battery source as needed to meet peak road power demands. In this manner, the flywheel acts to load-level the battery, thereby increasing its energy capacity to extend vehicle range. A variation on this concept would use a direct-mechanical, continuously variable transmission (CVT) to transfer flywheel power to the vehicle drive wheels.

In urban driving, the heat engine vehicle's fuel economy can be increased by as much as 35 percent with the flywheel. In highway driving, the flywheel offers no benefits.

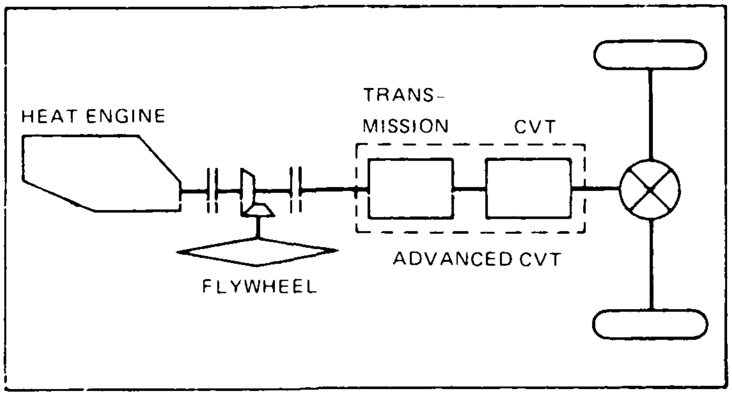

Figure 15. Heat engine/flywheel drive train: series arrangement.

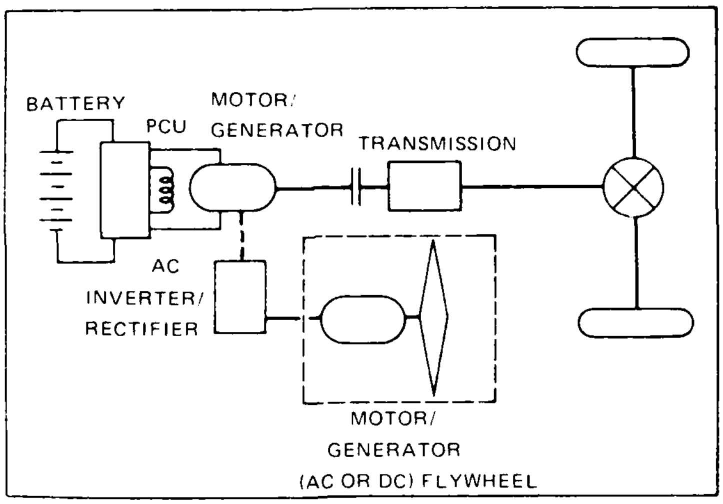

Figure 16. Battery/flywheel drive train: electrical power transfer.

Battery/flywheel vehicle designs incorporating new technology flywheel systems (hermetically sealed flywheel generators) do not provide measurable benefits in range relative to all-electric vehicles equipped with the same battery pack. Redesign of the flywheel battery system to trade off power for increased energy capacity substantially increases range beyond the capability of the all-electric vehicle equipped with conventional traction batteries (in some cases, tripling the range). The redesigned battery pack generally produces greater range in the all-electric vehicle, primarily because of its lighter weight. Properly configured, however, the flywheel system will improve performance in short-duration road maneuvers such as standing-start acceleration, merging, and passing. These results indicate that flywheels could have a significant conservation impact on vehicles that operate in an urban driving type of environment.

Flywheel energy storage systems have also been examined in conjunction with residential photovoltaic (PV) systems [86] (Figure 17). System simulation results indicate that the flywheel is a very important component. Flywheel use, defined as the percentage of time the flywheel system is usefully operating (not at a minimum or maximum energy storage state), is 77 percent for the case presented here. Overall system efficiency is 80 percent. (Overall efficiency is defined as the ratio of the kWh provided to theload to the sum of the PV array output and the purchased power, expressed as a percent.) On the average, the flywheel operates at its mid-energy storage capacity, actually 51 percent. System losses, purchased power, and power sold to the utility are 20 percent, 21 percent, and 5.4 percent, respectively, of the residential load.

Some very dramatic changes in the utility's load demand (Figure 18) are possible when a house is equipped with a PV array and a flywheel energy storage system. On the average, the maximum demand of the residence at 8:30 p.m. (20.5 h), the time of utility system peak demand, is reduced by a factor of five. Also, the average power demand over the day is lowered by about the same factor. The ability of the flywheel storage unit to reduce the peak demand of the utility is therefore significant and could be of great economic value when demand charges are high.

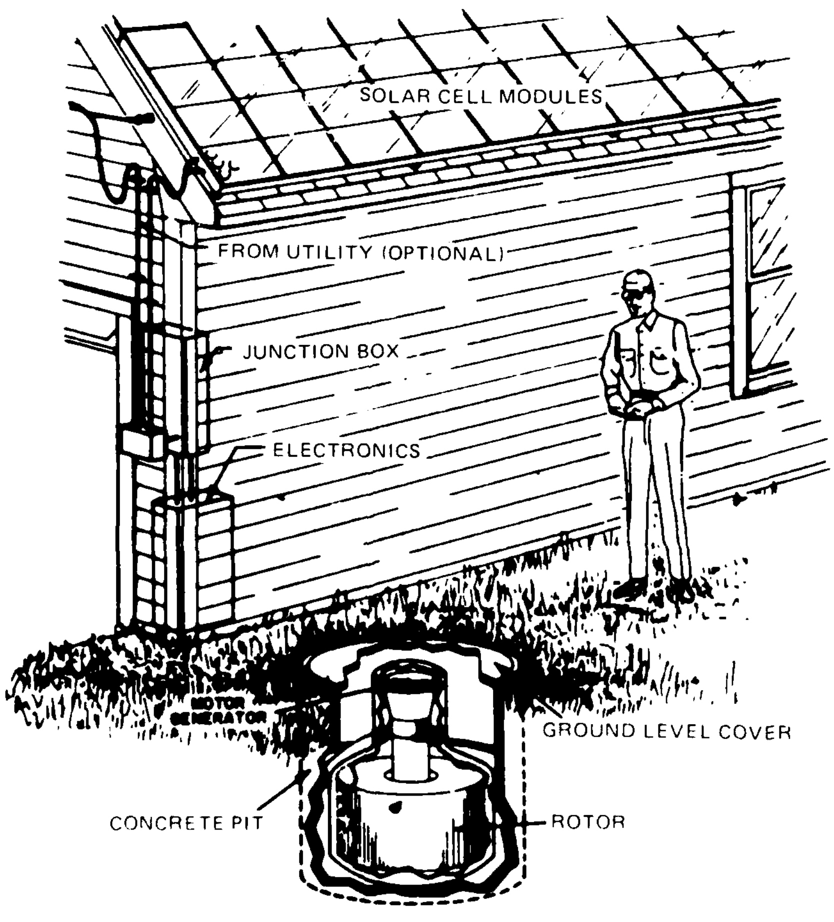

Figure 17. Residential photovoltaic flywheel system.

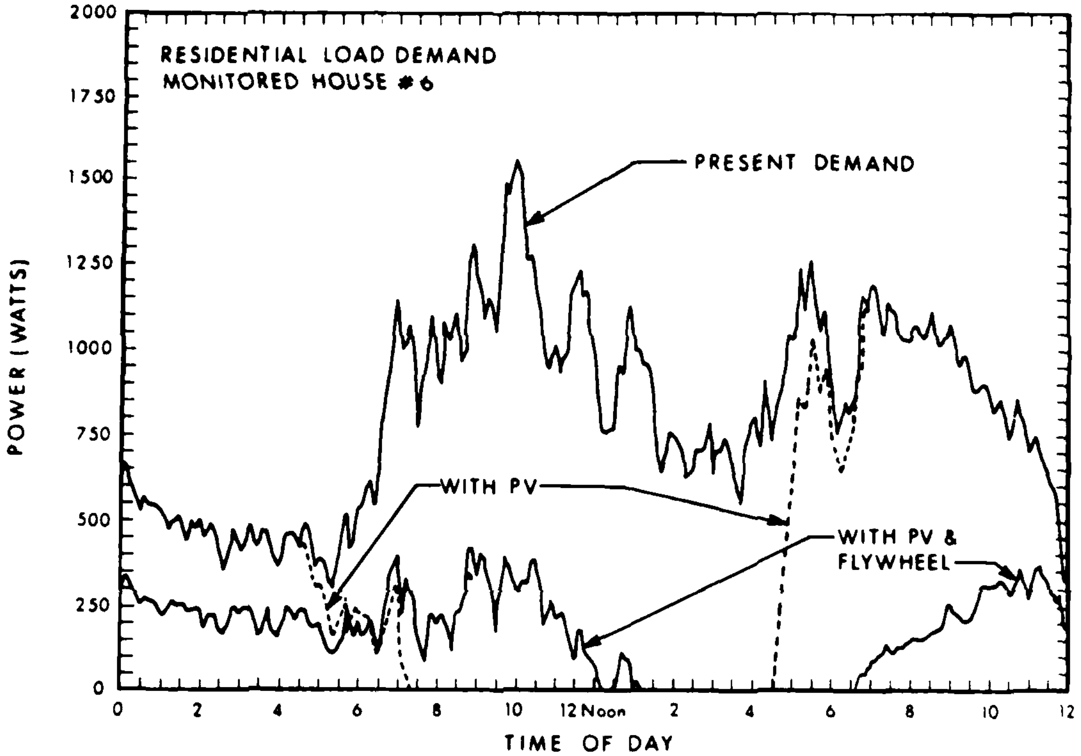

Figure 18. Residential load demand from utility—with and without 20-kWh flywheel energy storage system.

The last application area that has received attention is large fixed-base systems for industrial or utility use. In industries where demand charges are a significant portion of the utility bill, a flywheel system can be used to store energy during periods of low electric demand. Energy can be withdrawn from the store during peak demand periods, reducing the amount required from the utility. Current flywheel designs may be economically viable if demand charges are high. However, analysis of the specific application is required to determine the economic position of flywheel energy storage.

The use of flywheels to meet short-term (2-hr) utility peak demands has been investigated [83]. In general, current systems have been found to not be economically viable with combustion turbines for this application. However, further R&D could make flywheels more economically competitive.

Pumped Hydroelectric Energy Storage

Pumped hydroelectric storage is used by several utilities. Conceptually, a pump is used during low electric demand to pump water from a source reservoir to an elevated storage reservoir. During high electric demand, the stored water is released and the pump, which is reversible and can also act as a turbine generator, generates electricity. Surface pumped storage is highly site-specific. To drive the turbine generator, a large source of water must be available, as well as an adequate water storage reservoir at a sufficient elevation above the water source. Furthermore, the water source and storage reservoir must be in reasonably close to the source of electricity. When all these factors are considered, there are relatively few sites where pumped storage is feasible.

Because of siting constraints, underground pumped hydroelectric storage is generating interest among the utilities [77]. Underground pumped storage (Figure 19) is similar to surface pumped storage, but one reservoir and the pump/generator are underground. This concept is not limited by the topographic siting difficulties associated with surface storage. The excavated underground reservoir is usually 3000 to 6000 ft below the surface. The economics of underground pumped storage are favorably influenced by the resulting high operating head.

A study conducted for the Bureau of Reclamation's underground pumped storage program reviewed the current technology and evaluated technical feasibility and economic viability [78]. Criteria of 2000 MW capacity, 3600 ft head, and 10 hr storage were used. Three potential reservoir/powerhouse schemes were identified. Two were single-drop schemes, with one based on multistage reversible units, and the other on tandem units with separate multistage pump and Pelton impulse turbine. The third scheme was a double-drop type based on the use of an intermediate powerhouse and a small intermediate reservoir at about half depth. This scheme used single-stage, reversible pump-turbines. Table 9 compares estimated installation costs from this study with actual costs of existing surface pumped storage projects. Costs were adjusted to July 1978, and no allowance was included for interest during construction. The table shows that estimated costs for underground pumped storage lie between the two highest and two lowest values for conventional pumped storage.

There are currently no underground pumped storage systems in the United States.

Electric Energy Storage Systems

Two techniques have been considered for storing electric energy directly: superconducting magnets and batteries.

A superconducting magnetic storage system stores electric energy in the magnetic field produced by a circulating current in the windings of the magnet. To be superconducting, the windings must be cooled to a temperature near absolute zero. A 30-MV superconducting magnetic energy storage system has been built and installed in the Bonneville Power Administration system [76] under Department of Energy sponsorship.

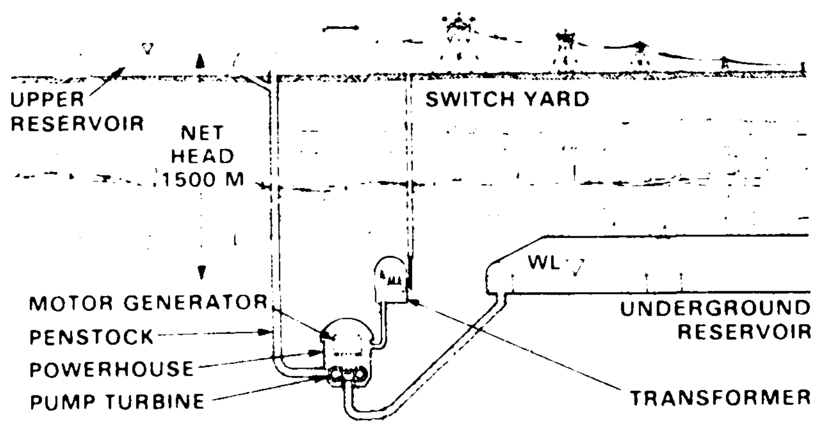

Figure 19. Schematic underground pumped storage installation.

Table 9

Comparison of Costs for Underground Pumped Storage and Conventional Pumped Storage

Plant or Configuration	Cost ($/kW)
Conventional	
Bear Swamp, MA	265
Ludington, MI	319
Boyd Co., NE	444
Bath Co., VA	459
Underground pumped storage	
Single-drop, multistage reversible P/T	356-379
Double-drop, single-stage reversible P/T	378-391
Single-drop, tandem impulse turbine and multistage pump	398-412

Its purpose is to damp oscillations of 0.35 Hz observed during high-power transmissions in the system. In this application, the system charges and discharges at the same frequency. Liquid helium cools the windings. Despite this experiment, superconducting magnetic energy storage must be considered to be very much in the early stages of development, and economical only in very large sizes.

Batteries have been used for electrochemical storage for more than 100 years. The increased interest in energy storage capability either on a large scale (as in utility storage) or on a smaller scale (as in uninterruptible power systems) has increased the interest in battery systems. Batteries are presently used as a backup power source in installations requiring an uninterruptible power supply (UPS). These applications, which range from hospital operating rooms to computer systems, are areas where the safety and reliability of electric power availability or the need for continuous power from an interruptible source, such as solar, outweigh the cost of the batteries. In large-scale battery storage applications, either for the utility or the customer, the economic attractiveness is determined not only by the battery costs and life, but also by the availability of low-cost, off-peak power at a favorable differential from on-peak power. While a few possible economically favorable applications have been examined, there has not been enough economic incentive to accept the risks of a new installation. Thus, there have been neither utility nor customer-side installations.

Batteries have many features that make them attractive energy storage options. They store high-quality power with efficiencies of 65 to 75 percent, and would require very short lead time from installation. In comparison to other storage systems (e.g., pumped hydro, compressed air), a battery system has moderate land requirements, thus reducing the environmental effects associated with installation and operation. The battery storage "footprint" is about 8 to 20 kWh/sq ft. Batteries are manufactured in discrete units that can be assembled in arrays to form a storage system of any desired capacity. This modularity allows easy expansion of an existing system as conditions

warrant. Battery storage can be used in applications similar to other large-scale storage systems; however, since they are modular, they can also be used in much smaller-scale applications with a less severe economic penalty. Thus, remotely sited battery storage is possible, and can reduce transmission and distribution costs.

As shown in Figure 20, a complete battery storage system requires several auxiliary systems besides the batteries themselves. All battery systems include three major components: (1) the converter, used to convert AC power to DC and vice versa, depending on the operating mode of the system, (2) the batteries themselves, used to store the energy, and (3) auxiliary systems used to support the converter and batteries. These can consist of cooling systems, ventilation systems, instrumentation, and the building itself, although not all of these are required for every battery type.

Batteries are made up of a number of cells connected electrically in series, in parallel, or in series-parallel. The cell is the basic electrochemical unit and contains the active materials that store chemical energy and determine the battery's characteristics. The electrochemical system determines the cell voltage, the quantity of active materials in the cell determines the amount of energy stored, and the cell design determines the rate at which energy can be withdrawn. While the characteristics of various electrochemical systems can differ considerably, there are certain common characteristics of battery behavior.

The charge-discharge cycle is not perfectly reversible. Repeated charge-discharge cycling causes irreversible changes in the cell that tend to degrade cell performance, so a battery has a finite useful life. Some side reactions may also occur other than the charge-discharge reaction, reducing cell performance. Internal resistance within the battery cell causes required charging voltage to be higher than discharge voltage. Self-discharge also occurs due to local chemical processes. All of these factors reduce cell and battery efficiency. Expected battery efficiencies are 65 to 75 percent.

Other battery characteristics also affect storage performance. The higher the discharge rate, the lower the cell voltage. Increased depth of discharge decreases cell life. Increased temperature can decrease cell life and require higher charge input. However, increased temperature also increases discharge capacity.

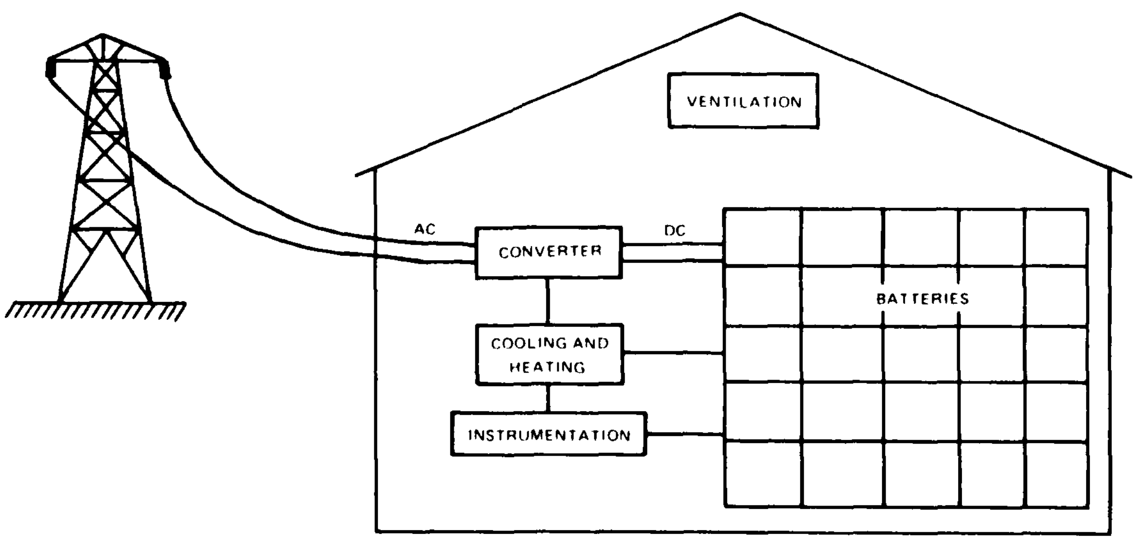

Figure 20. Schematic of battery storage system.

Several types of batteries have been proposed as potentially useful for large-scale energy storage systems: lead-acid, zinc-chloride, zinc-bromine, sodium-sulfur, and lithium-metal sulfide.

Lead-Acid

Only the lead-acid battery is commercially available. Lead-acid cells can be designed and produced with existing technology to provide the longevity and deep discharge characteristics needed for large-scale energy storage systems. Characteristics of the lead-acid system have been determined from a large amount of operating experience. These batteries are currently used in several applications, including uninterruptible power systems, industrial equipment, and power systems for diesel submarines. Adaptation of lead-acid cells to large-scale storage systems would require only minor design changes.

The charge-discharge reaction in the lead-acid cells is commonly written as:

$$Pb + PbO_2 + 2\ H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} 2\ PbSO_4 + 2\ H_2O$$

Lead dioxide (PbO_2) is the cathode and sponge lead (Pb) is the anode. The electrolyte is a solution of sulfuric acid (H_2SO_4) in water. These cells generally operate at near ambient conditions (20^o to 30^oC); however, they may require some means of auxiliary cooling to prolong system life. Cooling is either by forced air or water circulation. Most lead-acid storage systems would also require a ventilation system to prevent the build-up of explosive mixtures of hydrogen (formed on overcharging) and to eliminate arsine and stibine which may be formed by side reactions. Some cell designs will require some form of electrolyte agitation during charging operations, since the electrolyte may tend to become stratified within the cell. Airlift pumps are often specified for this purpose.

Lead-acid batteries also require periodic equalization charges to balance cells in the battery string, since after a series of charge-discharge cycles, individual cell performance begins to limit charge and discharge operations; i.e., voltage, specific gravity, etc., may begin to differ from cell to cell.

The original cost of a long-cycle-life, lead-acid battery is estimated at $125 to $200 per kWh, depending on the discharge time, with one replacement battery costing about $100/kWh over the 20-year life of a 100-MWh plant. The battery salvage value of end-of-life is largely the value of recovered lead and antimony and is about $12 to $18/kWh. Maintenance costs are usually limited to costs for water addition, cleaning of cells, and replacement of dead cells. These costs are small, amounting to $0.4 to $4.0/kWh/year [62] (values are for 5 hr discharge duration and 40 to 80 percent depth of discharge batteries).

Some improvement in lead-acid battery performance may be possible using various material, process, and design changes; however, the improvements are not expected to make lead-acid cells economically attractive in the near future for large-scale storage systems.*

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*Information presented on lead acid batteries has been compiled from several sources (see Refs. 63, 64, and 65).

Other battery types have been proposed as potentially useful for large-scale energy storage. Some have been developed to the prototype stage, but none are commercially available yet. The following descriptions are therefore for batteries which are, at best, only near-term prospects.

Zinc-Chloride

The zinc-chloride battery uses a circulating liquid electrolyte of zinc chloride and water. Zinc is the anode, and dissolved chlorine is the cathode. The charge-discharge reaction is written as:

$$Zn + Cl_2 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} ZnCl_2$$

The chlorine is stored as chlorine hydrate, an ice-like solid. During charging, zinc is plated on the anode, and the chlorine gas evolved at the cathode is dissolved in the circulating electrolyte. The electrolyte then passes through a heat exchanger where it is chilled sufficiently to precipitate chlorine hydrate, which goes into a storage tank. On discharge, heat must be applied to release the chlorine from the hydrate to the electrolyte. The electrolyte then passes through the cathode where the chlorine reacts with it. Besides the battery stack, system components include pump, valves, heat exchangers, and refrigeration equipment, so the system is much more complex than a conventional battery system and may be less reliable. Since zinc-chloride batteries can release chlorine, most installations would require some type of ventilation system.

Battery cost estimates have been made which assume that a production facility would be built which produces 16- to 100-MWh per year. The battery cost was estimated to be \$28/KWh [66]. One replacement of the battery system during plant lifetime would cost an additional \$26/kWh. Although the salvage value of end-of-life batteries is not known exactly, it is estimated that 3 to 10 percent of original value is probably reasonable. Maintenance costs for zinc-chloride batteries are perhaps somewhat less than for the lead-acid batteries, since no water addition is normally required. However, battery replacement and cleaning would be needed, and it is estimated that total maintenance costs would still range from \$0.4 to \$3.00/kWh.

Zinc-Bromine

The zinc-bromine battery is very similar to the zinc-chloride battery, but is stored as a complex at room temperature. The electrolyte is a water and zinc-bromide solution. Zinc acts as the anode and bromide as the cathode. Construction of the cell consists of two separate-flowing electrolyte circuits: one flows past the positive electrode, and one flows past the negative electrode. These two circuits are separated within the cell itself by a microporous membrane that restricts the flow of electrolyte between compartments, but allows ionic crossflow between the separate streams. The two streams are separated to decrease the cell's tendency to self-discharge. Electrolyte circulation also provides a way to optimize electrolyte temperature, thus ensuring maximum cell performance and service.

The zinc-bromine battery requires the use of electrolyte pumps, storage tanks, and appropriate piping. Heat exchangers keep the operating temperature in the 50° to 60°C range for optimum cell performance. Each week, zinc-bromine batteries are expected to require a complete discharge to prevent zinc buildup on the electrodes.

In determining the cost of zinc-bromine batteries, assumptions about manufacturing and battery system size were made that were similar to those used in the zinc-chloride analysis. Original cost of the batteries is estimated to be ~$50/kWh [67]. One battery replacement would be required over the 20-year life of a plant. It is estimated that battery replacement would cost $30 to $45/kWh. Salvage value of the sealed battery would be low, as with the the zinc-chloride battery: 3 to 10 percent of original cost. Maintenance costs for sealed zinc-bromine batteries should be similar to those of zinc-chloride batteries, or $0.4 to $3.00/kWh.

Sodium-Sulfur

The sodium-sulfur battery operates at 300° to 350°C, using liquid sodium as the anode and molten sulfur as the cathode. A solid alumina electrolyte is used to separate the two molten electrodes. The appropriate cell reaction is written as:

$$2\ Na + XS \underset{charge}{\overset{discharge}{\rightleftarrows}} Na_2S_X$$

Sodium polysulfide composition changes as the degree of charge/discharge changes. The value for X varies from 2 to 3.

Thermal control of the battery system is required to keep the cell at proper operating temperature; heating is required during startup and idle periods, and cooling is needed during operation.

Since development and design of this battery are not complete, costs are not well-defined. However, an estimate of $100/kWh for original batteries, and one replacement, is probably reasonable. Maintenance costs similar to those of the zinc-chloride battery are also expected.

Lithium-Metal Sulfide

Lithium-metal sulfide batteries are the least developed of any type described here. They will use either lithium-aluminum or lithium-silicon alloy as the anode and iron sulfide (FeS) or iron disulfide (FeS_2) as the cathode. The electrolyte will be a mixture of lithium chloride and potassium chloride. The overall reaction for the lithium metal sulfide cell can be written as:

FeS_2 reaction $\quad 2\ LiAl + FeS_2 \rightleftarrows Li_2S + FeS + 2Al$

FeS reaction $\quad 2\ LiAl + FeS \rightleftarrows Li_2S + Fe + 2Al$

Battery operating temperature is 400° to 500°C to ensure that the electrolyte remains liquid.

As with the sodium-sulfur cell, cooling and heating requirements have not been completely estimated. Costs are expected to be $100 to $150/kWh, with maintenance costs similar to those of the sodium-sulfur battery.

Discussion

Conversion equipment for each of the battery types will be very similar. The system must convert AC to DC voltage and vice versa. This includes voltage and impedance correction if necessary. Costs should be very similar for any battery system, and will range from \$50 to \$150/kW. The zinc-chloride system may require less voltage correction than the other systems and may therefore be at the lower end of this cost range.

Other auxiliary systems required will differ for each battery type and may include controls for the charge/discharge rate, cooling/heating systems and controls, automatic water addition, system monitors, ventilation, electrical bus work, electrical protection (fusing, etc.), fire equipment, and containment building.

The costs of these will vary among battery types and designs. For example, those systems that use free convection cooling will probably not require any further ventilation or a building enclosure. However, other systems would be required, such as tighter battery enclosures to keep out moisture. Therefore, the range of costs for auxiliary systems is estimated to be \$40 to \$120/kW [66,62].

Only one facility is currently available for testing large-scale battery storage systems. Electric Power Research Institute (EPRI), the Department of Energy, and the Public Service Electric and Gas Company of New Jersey sponsored development of the Battery Energy Storage Test (BEST) Facility which is to be used as a national center for testing advanced battery storage systems [68]. Only one battery has been installed to date. It is a 1.8-MWh lead-acid battery developed by C&D Batteries Division of Eltra Corporation and is used as the station operating battery. The first advanced battery scheduled to go into the facility is a zinc-chloride battery scheduled for delivery in late 1983. This battery was developed by Energy Development Associates. Table 10 lists other battery developers from the BEST Developer Users Group.

The cost of large-scale battery storage is currently prohibitively high. Table 11 summarizes battery costs and types. Advanced batteries with lower costs are, at best, near-term prospects. The only battery with technology now ready for production is the lead-acid battery. Although its costs are high for large-scale storage, it is now used for small-scale UPS and remote PV service. For battery storage systems to become economically attractive, low-cost batteries must be developed that meet the long-life requirements needed for large-scale storage systems.

Table 10

Participating Organizations in BEST Facility Developer Users Group

AiResearch Manufacturing Co. of California	General Electric Company
Argonne National Laboratory	Globe-Union, Inc.
Brown Boveri & CIE	Gould, Inc.
C & D Batteries Division	Hooker Chemical Corporation
DOW Chemical	Public Service Electric and Gas Company
Eagle Picher Industries, Inc.	Rockwell International Corporation
Energy Development Associates	United Technologies Corporation
ESB Technology Company	Westinghouse Electric Corporation
Factory Mutual Research Corporation	
Ford Aerospace & Communication Corporation	

Table 11

Listing of Battery Costs

Battery Type	Developer	Estimated Battery Cost (20-Year Plan) ($/kWh)	Converter Cost ($/kW)	Auxiliary Cost ($/kW)	Technology Ready
Lead-acid	C&D Batteries Division	300*	50-150	40-120	Present
Zinc-chloride	Energy Development Associates	55**	50-150	40-120	1986-1987
Zinc-bromine	Exxon	90**	50-150	40-120	1986-1987
Sodium-sulfur	GE and Ford	100***	50-150	40-120	1987
Lithium-metal sulfide	Argonne National Laboratory	150***	50-150	40-120	1987

*1982 dollars.
**1977 dollars.
***1979 dollars.

3 DESCRIPTION OF ANNUAL CYCLE THERMAL ENERGY STORAGE

Storage of thermal energy on an annual cycle implies that a single charge/discharge cycle of the storage facility takes place over 1 year. Obviously, the storage reservoir must be very large to accommodate the heat or cold that is handled over this period. Also, the storage medium must be very cheap. Probably the most attractive storage reservoir for annual cycle storage is the underground aquifer whose storage medium is water and earth. Other reservoirs that have been considered are lakes, ponds, caverns, tanks, and earth. The storage medium for all these concepts is either water or earth. This section discusses aquifer storage, "nonaquifer" storage, which includes the other concepts listed above, and an annual storage cycle involving the generation and storage of ice.

The annual energy storage cycle is generally considered with energy sources and applications that are displaced seasonally in time. Without annual storage, these sources would be wasted or unavailable, because there would be no demand at the time of availability. Annual storage is not of interest for electric load management, which is a diurnal phenomenon. Examples of energy sources where annual storage is appropriate are:

1. Storage of waste heat--for example, the storage of heat which is available all year from laundries, dining halls, or incinerators. The stored heat could be used for building heating or domestic hot water.

2. Storage of winter chill for summer air conditioning

3. Storage of hot water from a cogeneration plant for building heating.

Generally the annual storage cycle is considered to be most appropriate for large energy sources and large applications where the economies of scale can be used to increase the thermal- and cost-effectiveness. For example, the annual storage cycle is often considered with district heating applications.

Aquifer Storage

Figure 21 shows an aquifier storage installation [26,27]. Here, the energy source is waste heat from an industrial plant, although any of the previously mentioned sources could be used, and the application is district heating. Water is withdrawn, heated, and reinjected into the aquifer with two conventional water wells that are separated enough that they will not interact. During the charging cycle, warm water is withdrawn from the aquifer, heated in a heat exchanger with waste heat from the plant, and reinjected in the hot storage zone. During the discharge cycle, hot water is withdrawn from storage, used to heat water for the district heating system, and reinjected in the warm storage zone. During the year, the district heating system may require no hot water (all waste heat into storage) or any combination of stored hot water plus heat. Thus, a valving and control system is required to shuttle the water flows in the correct directions to meet system demands, and at the same time store the excess heat. Larger installations would require multiple wells.

An aquifer is a geologic stratum of either permeable rock or unconsolidated sediment that contains and transports water. To be useful for storage, an aquifer should be confined; that is, it should be bounded above and below with a layer of impermeable rock to prevent vertical transport of water. Also, the natural lateral water flow must be

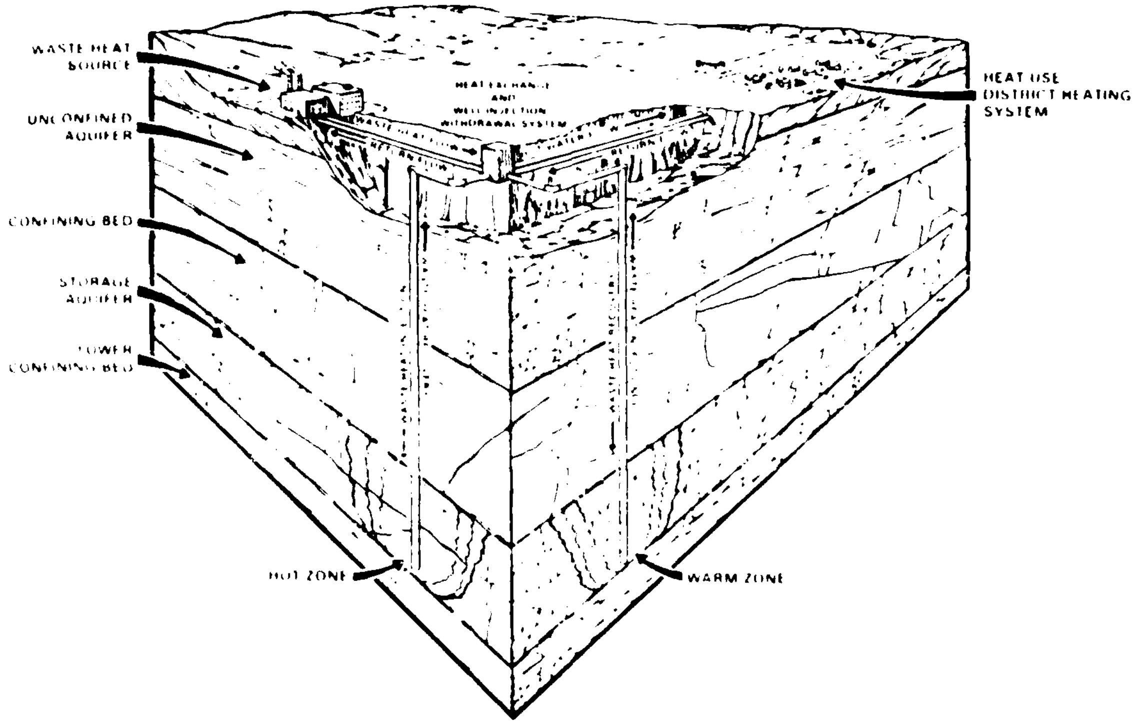


Figure 21. Aquifer thermal energy storage.

low. The water pressure in an aquifer is determined by the elevation of the source water for recharge, which may be considerably removed from the storage site being considered. Appropriate aquifer depths are likely to be 150 to 1500 ft--deep enough to prevent interaction with surface water, but not so deep as to make drilling and pumping costs prohibitive.

Aquifers are common in the United States. For any specific site, subsurface exploration involving drilling, core sampling and testing, and hydrologic testing will be necessary to show suitable aquifer characteristics.

It is usually considered undesirable to charge an aquifer with foreign water. This can cause plugging with particulate fines, contamination and subsequent plugging from sulfate-reducing or iron-oxidizing bacteria, or chemical reaction of the foreign water with the aquifer matrix, which can cause plugging or some other matrix decay mechanism. Usually these problems can be handled periodically by chemical and bactericide additions. A better solution is to withdraw water from the aquifer, heat it (or cool it) with a heat exchanger, and reinject it into the same aquifer at a different location. Thus, in considering aquifer storage, the use of heat exchangers should be assumed until it is shown conclusively that they are not required.

Figure 22 illustrates typical thermal performance of an aquifer storage system [28]. The data shown are the result of a computer simulation using the CCC (conduction-convection-consolidation) three-dimensional, finite-difference numerical model developed at Lawrence Berkeley Laboratory. In this example, cold water at 39°F was pumped continuously at 180 gpm into an aquifer for 90 days. It was then stored for 90 days. After the storage period, it was extracted for 90 days at the same flow rate (180 gpm). This cycle was repeated four times. Figure 22 shows the water temperature during the extraction cycle. Note that after several days, the water temperature starts creeping

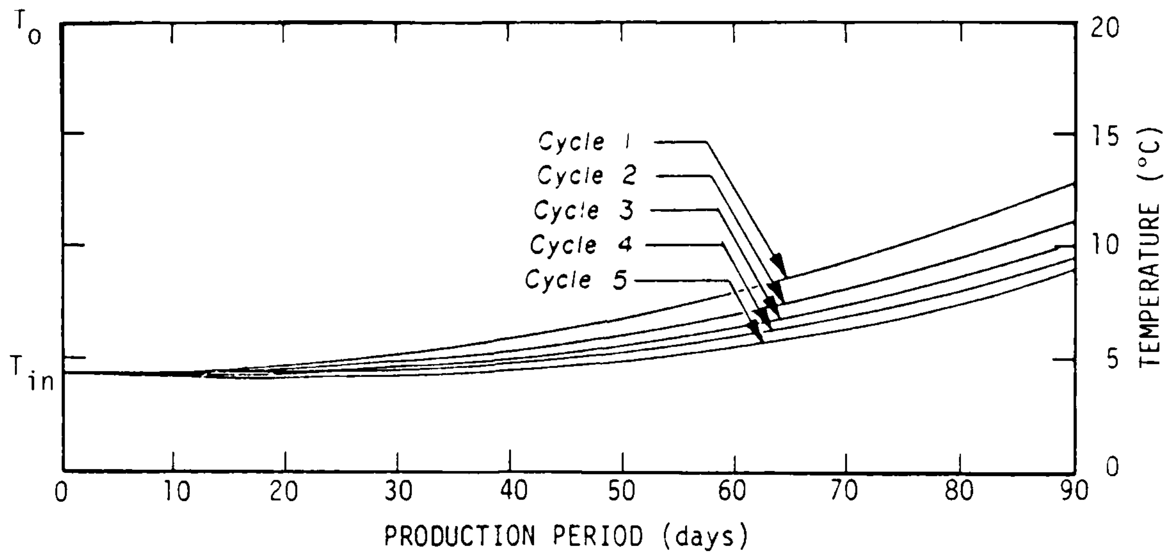


Figure 22. Production temperature of cold water as it is recovered from storage in an aquifer.

up, and at the end of the first cycle is up to 55°F. Much of the cold that was injected during the first cycle remains in the aquifer at the end of the first recovery. This pre-cools the aquifer so that the recovery after the second cycle is a little more efficient. This phenomenon continues after each cycle until after about five cycles, when the aquifer has almost reached steady state. The performance characteristics for hot water are essentially the same as for cold water. The aquifer used in the above simulation was an ideal aquifer. Real aquifers may contain low permeability material extending out of the storage zone and possible leaky containment strata, both of which would tend to degrade performance.

Several federally supported aquifer field test facilities have been built and operated in the United States [29,30,31]. There is at least one privately constructed aquifer storage facility in the United States. The Parisian is a 60,000 sq ft department store in Tuscaloosa, AL, that has installed a "free cooling" system using annual cycle storage. The system uses a cooling tower during the winter to generate water at an average temperature of 43°F. The tower is operated when the wet-bulb temperature is 47°F or less. Cold water is stored in an unconfined aquifer for summer use. The system became operational in the Fall of 1981, and water chilling began in October of 1981. Several startup problems occurred, and the system was down for the two coldest months (December and January). Still, it was estimated that more than 10 million gal of cold water were stored. Most of the air-conditioning requirements during February, March, and April 1982 were met with stored cold water. Since then, water temperatures of 64° to 67°F have been carrying a base load of about 40 tons, with the backup air conditioner (200 tons) carrying the rest of the load. The coefficient of performance (COP) of the aquifer storage system was estimated to be about 9.0.

During charging of this system, water is withdrawn from the discharged storage area and passed through wet cooling towers where it is cooled and aerated. It is filtered through a sand filter before reinjection into the cold storage region. During discharge, the cold water passes directly through water-to-air cooling coils. The aquifer itself, which is about 40 ft thick, is unconfined and consists of diluvial deposits of sands and gravel. The wells are about 80 ft deep.

The economies of aquifer storage have been addressed primarily for large systems [33,34]. A computer program (AQUASTOR) has been developed [32] to conduct cost analyses of aquifer storage coupled with district heating or cooling systems. These studies indicate that the economics of aquifer storage are highly application-specific, and that those parameters which exhibit a substantial influence for heat storage are purchased thermal energy cost, cost of capital, source temperature, system size, transmission distance, and aquifer efficiency. The parameters that substantially influence the economies of cold storage are system size, well flow rate, transmission distance, source temperature, well depth, and cost of capital. In general, heat storage systems are more economical than cold storage systems. The main constraint on cold storage systems is the very low energy density of the storage fluid. For cold storage, the usable energy contained in 1 lb of water between 35° and 55°F is only 20 Btu. In comparison, the usable energy in hot water between 225° and 125°F is 100 Btu. Thus, the equipment for handling cold water must be much larger to deliver the same amount of energy.

The economics of aquifer storage for military applications may be entirely different. For example, district heating in the residential sector would involve much more complicated piping arrangements than troop barracks and administration buildings, the cost of waste energy may be handled entirely differently, and the cost of capital may be different.

Nonaquifer Storage

Although aquifer storage is predicted to be the most cost-effective technology for annual storage, suitable aquifers underlie only about 60 percent of the United States; thus, other methods of annual storage will be required where aquifers are not available or economically feasible. Other reservoirs that have been considered for sensible annual storage [26] include ponds, lakes, caverns, tanks, earth, and rock (Figure 23). These storage concepts would generally be appropriate for the same energy sources and applications as aquifer storage.

An additional storage reservoir that might be of particular interest to the military could be referred to as "reservoirs of opportunity." That is, there may be existing tanks or caverns on an Army post that were built for some other purpose that could be converted to a hot water storage tank at minimum cost. For example, the Navy has just completed a feasibility study [35,36] concerning the use of two existing underground concrete tanks at the Charleston Navy Yard in Boston for use in an annual storage cycle. The tanks were built in the 1950s for water and petroleum storage. Tank capacities are 127,000 cu ft. The concept involves collecting and storing solar-heated water on an annual cycle. Both tanks will be used for hot water storage. Hot water will be used for district heating of five buildings located near the tanks. The tanks alone will not meet the buildings' annual heating requirements, so it has been proposed that a heat pump be used to increase the tank capacity. When the storage temperature reaches 131°F, a heat pump will be activated that will draw the water temperature down to about 50°F.

Table 12 compares current technology level and development needs for each nonaquifer storage method.

Generally, the nonaquifer annual storage cycle reservoirs are not appropriate for a single residence. Figure 24 shows the approximate storage capacity (in home-equivalents) required to achieve cost- and thermal-effectiveness of these storage sytems. The sizing is necessarily rather crude and was generally based on costs of less than $15,000/ home, storage efficiencies greater than 70 percent, and size ranges available in the

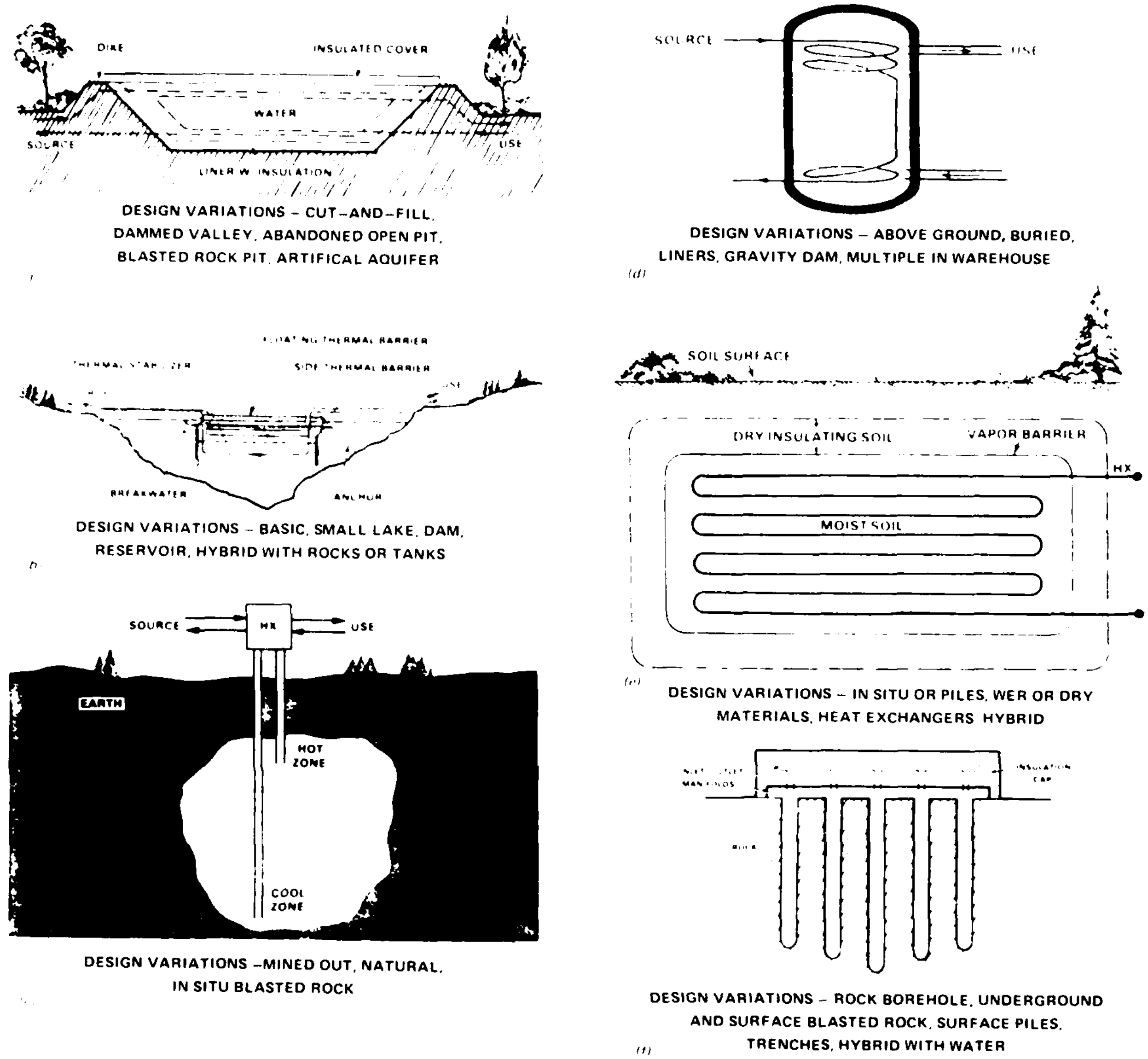


Figure 23. Annual energy storage methods.

literature. A nonaquifer storage system usually requires at least a home-equivalent capacity of 50 homes to be feasible. Tankage and pond storage may have potential for fewer than 50 homes at some sites; in comparison, an aquifer storage system would probably be sized between 75 and 2000 homes.

Capital costs of nonaquifer storage components are high at the low end of the capacity range, and low of the high end, as shown in Figure 25. Costs can vary substantially and probably extend beyond the ranges shown. Nevertheless, this figure shows typical ranges. These costs are for storage components alone, and do not include source, use and thermal transport system expenses. By comparison, the equivalent capital cost for an aquifer storage system would range from \$20 to \$200/10^6 Btu, and would generally be lower than nonaquifer costs.

Table 12

Nonaquifer Storage Concept Technology Assessment

Concept	Relative State of Technology	Development Needs
Pond	Good	Liner and insulation
Lake	Poor	Insulation/liner system and environmental effects
Cavern	Fair	Lining and insulation methods, chemical and thermal cycling effects
Tank	Excellent	Tank and insulation cost reduction
Earth	Fair/Good	In-situ heat exchange and insulation methods
Rock Borehole	Fair	Drilling cost reduction and lining methods

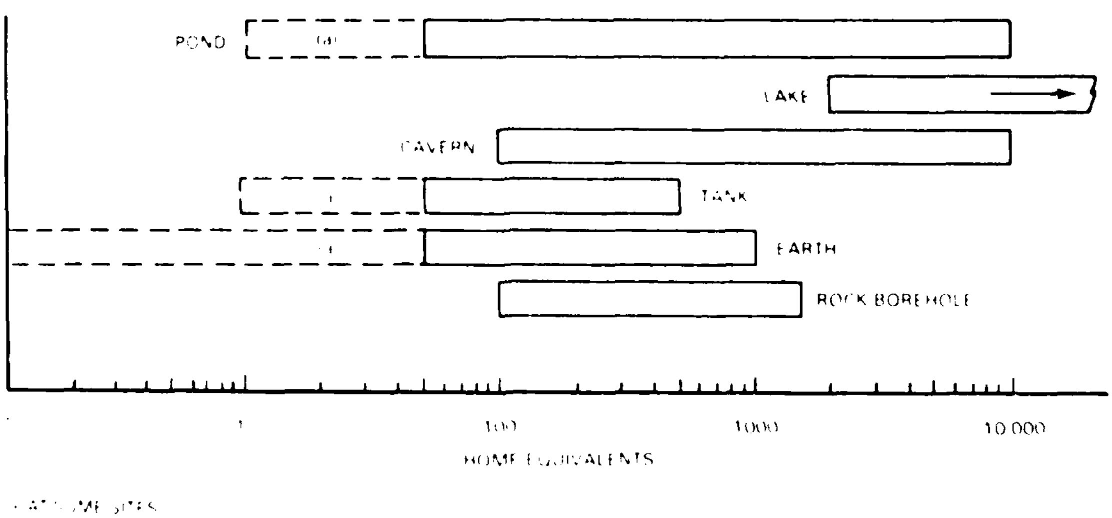


Figure 24. Home equivalent capacity required.

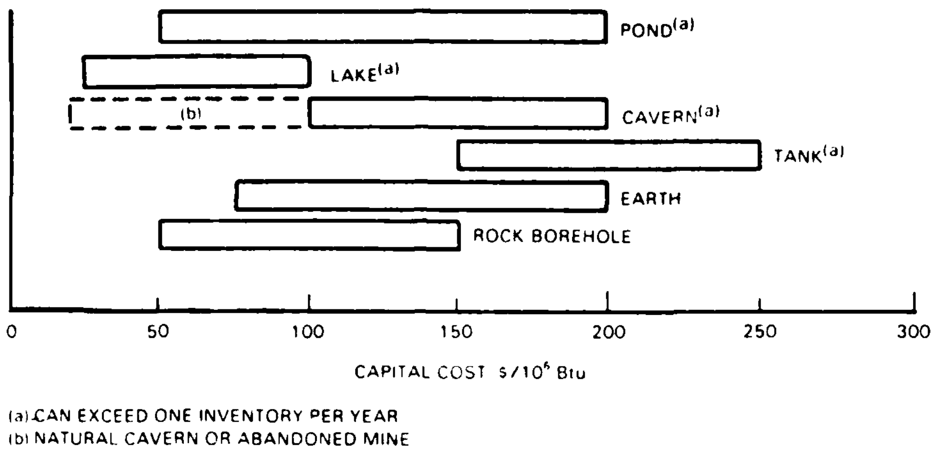


Figure 25. Approximate capital cost.

Ice Storage

Two annual ice storage concepts are examined in this report. The first is usually referred to as the ACES (Annual Cycle Energy System) concept. Here, ice is generated during the winter months with a heat pump. The reject heat (144 Btu/lb of ice) is used for building heating. The ice is stored in a vault for air conditioning the building the following summer. In the second concept, ice is generated during the winter by exposing water to ambient outdoor temperatures. The ice is then stored for air conditioning during the following summer.

Figure 26 shows the first test of the ACES concept, which was conducted in an unoccupied experimental residence [37,38] in Knoxville, TN. The system is designed to supply space heating, hot water, and air conditioning. Basically, heat is supplied during the winter by freezing ice in the ice bin, which in this case took up about half the basement. The reject heat is pumped up to a suitable temperature by the heat pump and is used for space heating. The ice is stored and used for air conditioning the following summer. In this version, the ice is generated and stored as logs around tubes supported in a serpentine manner in the ice bin. An ice shucker could also be used. Hot water can be generated simultaneously, while meeting building heating requirements, or separately, during the summer. The ACES system performs best in climatic regions where ice formed during the heating season matches the summer cooling requirements. In colder climates, more ice will be formed than required for air conditioning. Conversely, in warmer climates, insufficient ice will be formed to meet air-conditioning requirements. Thus, in designing an ACES, provisions must be made for melting excess ice, and for supplemental air conditioning when there are ice deficits. Excess ice is melted by pumping cold water from the ice bin through solar collectors. Additional air conditioning can be supplied by operating the chiller during periods of off-peak rates or low electrical demand. For these reasons, ACES performance is regional; and Figure 27 shows the annual COP that can be anticipated over the United States.

The chiller consists of a compressor, desuperheater, two condensers, and an evaporator. They are all tightly coupled in the mechanical equipment package. Thermal transport to the ice bin, fan coil, and solar collector panel is with methanol brine, and

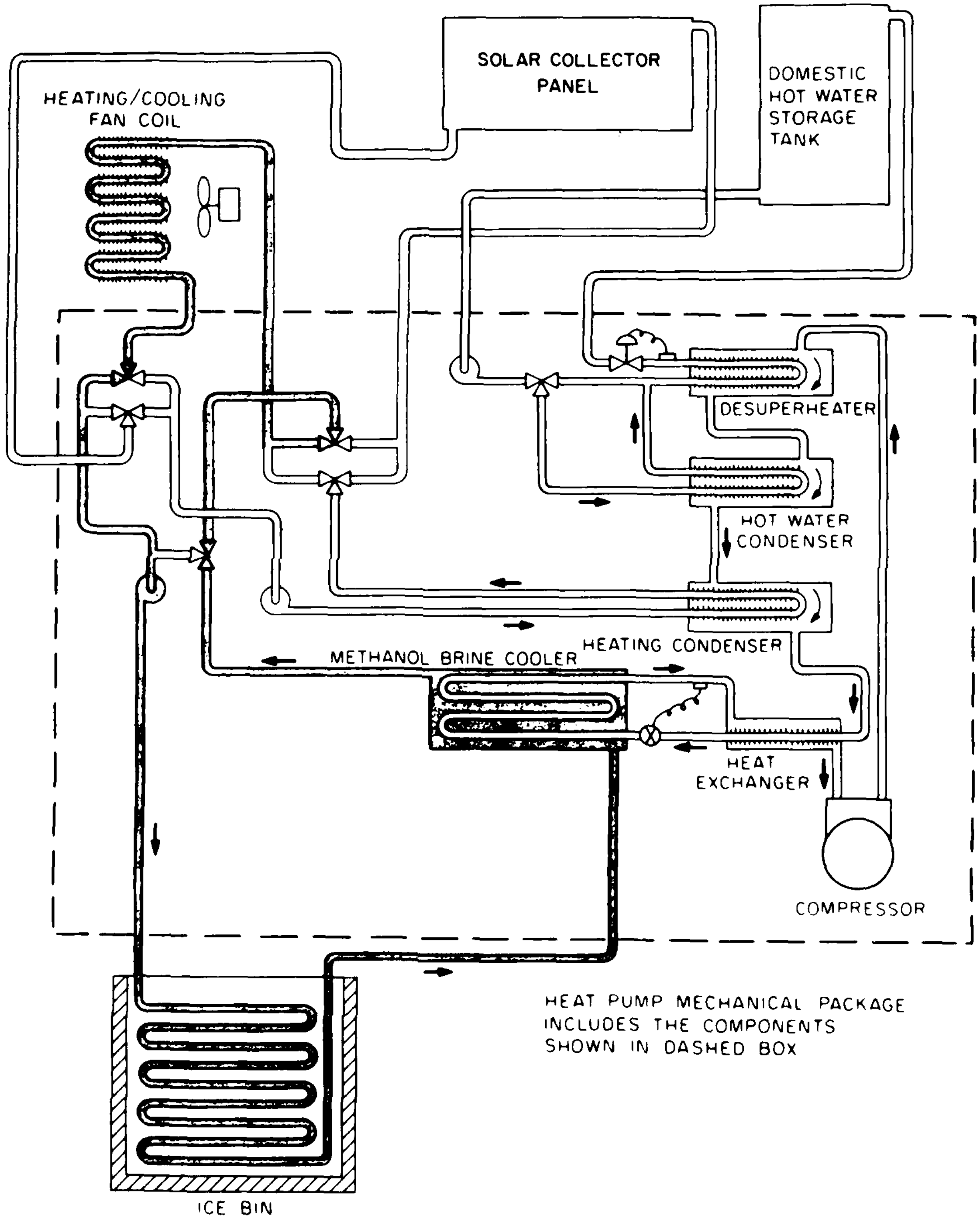


Figure 26. Schematic of ACES.

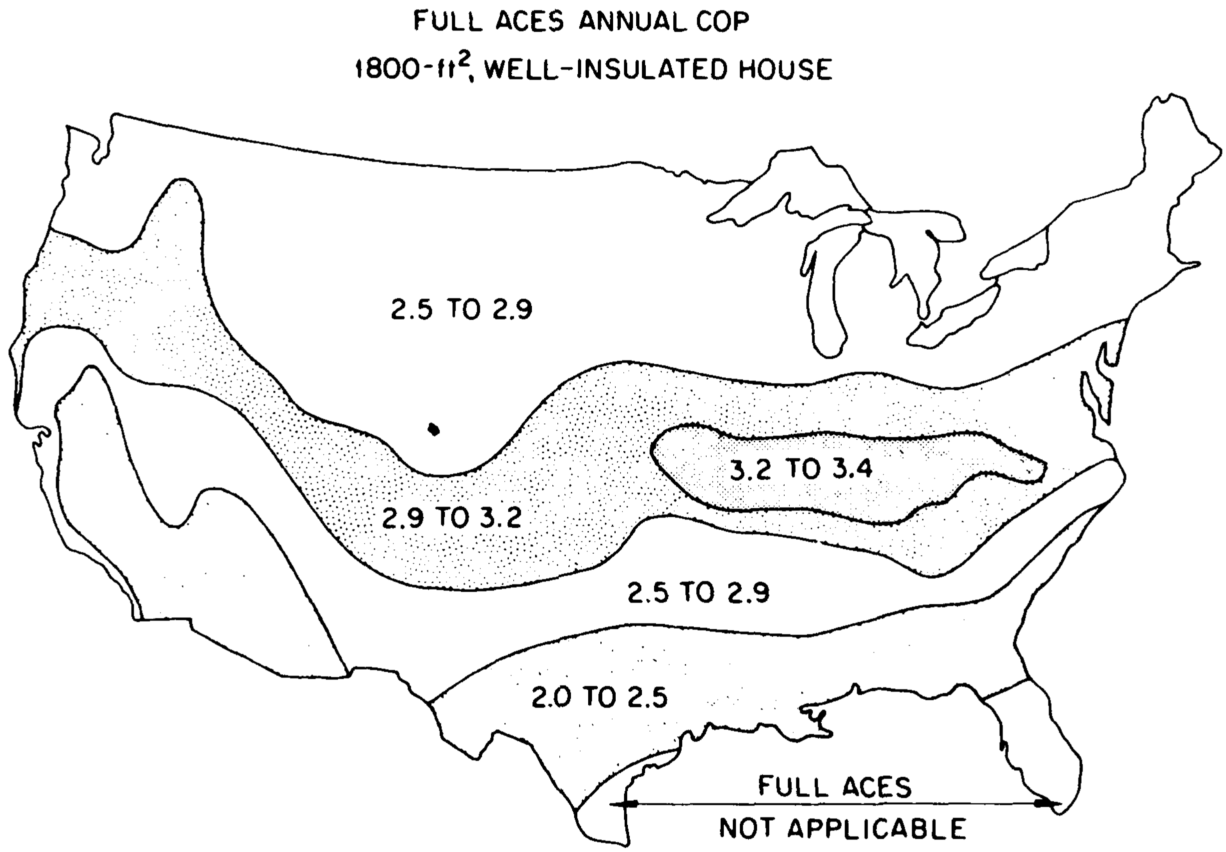


Figure 27. Region of full ACES applicability.

thermal transport to the hot water tank is with water. The total system must be able to operate in five modes: (1) hot water production, (2) space heating and water heating, (3) space cooling from the ice bin, (4) supplemental air conditioning, and (5) environmental energy collection to melt excess ice. Thus, the system is complex, and contains a number of pumps, control valves, and control circuitry.

The ACES concept described above is referred to as the "full" ACES, and is designed to maximize interseasonal energy transfer. The ice storage bin is sized to hold all the ice formed in the winter, or that amount of ice required for air conditioning, whichever is smaller. Another ACES concept referred to as the "minimum" ACES has a storage bin just large enough to supply the total space and water heating loads for the two coldest weeks of the winter without operation of the solar collector panels. Of course, any system between "full" and "minimum" may be considered. The intent of storage bins of less than "full" size is to reduce the cost of the storage bin, which is the system's greatest single cost.

Figure 28 gives the results of a detailed study of the economies of ACES and other heating systems for the residential application [39]. Conclusions from this figure are that for most parts of the country, the first cost of an ACES system is more than twice that of a conventional heating and cooling system. Annual energy consumption is less than for other heating and cooling systems except in the deep south, where cooling needs so greatly exceed heating needs that little interseasonal energy transfer is possible. Because of the high first cost, the total life-cycle cost of the ACES generally exceeds that of more conventional heating and cooling systems. It is likely that the economies of ACES would be more attractive at large installations subject to electric demand charges.

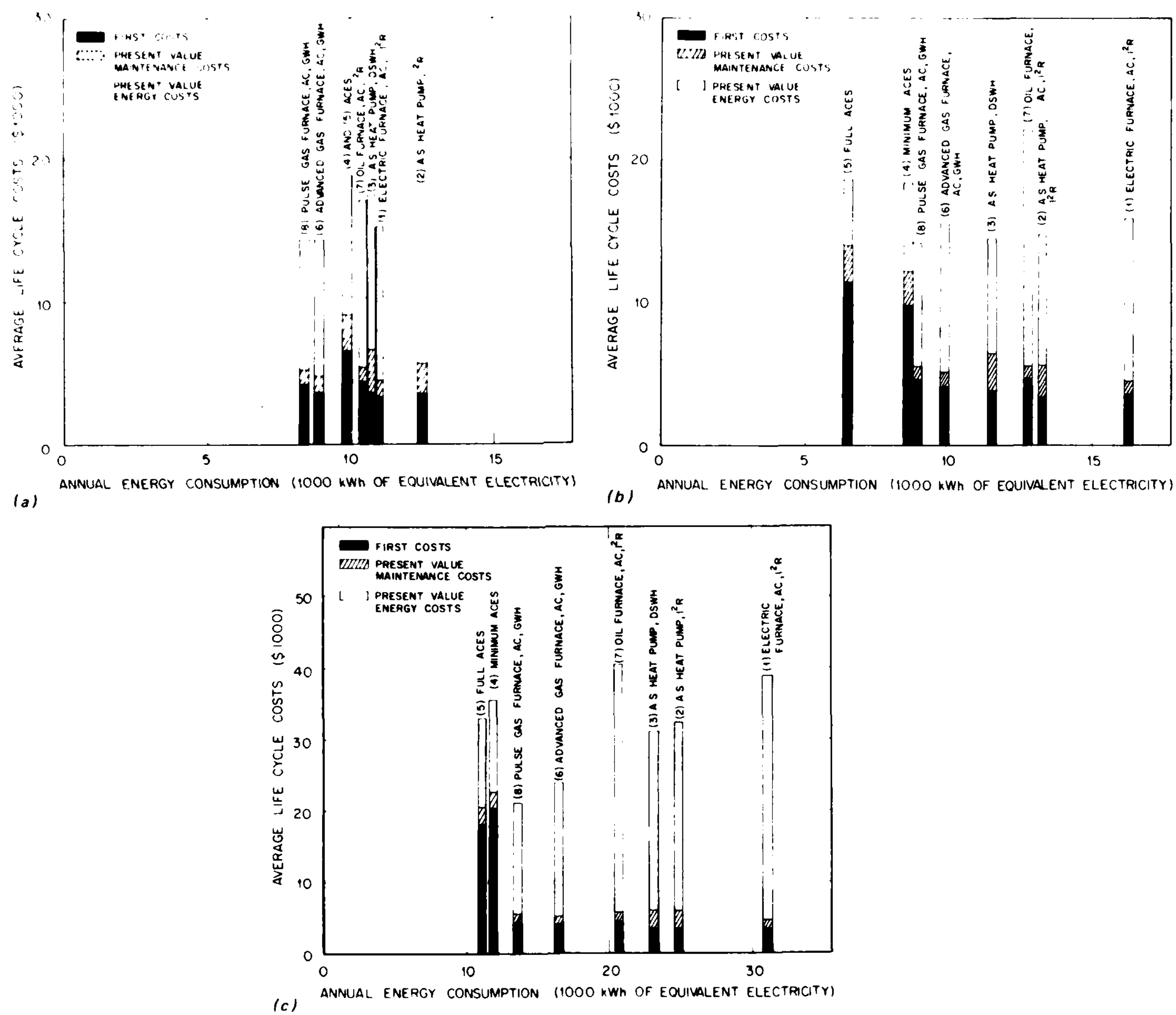
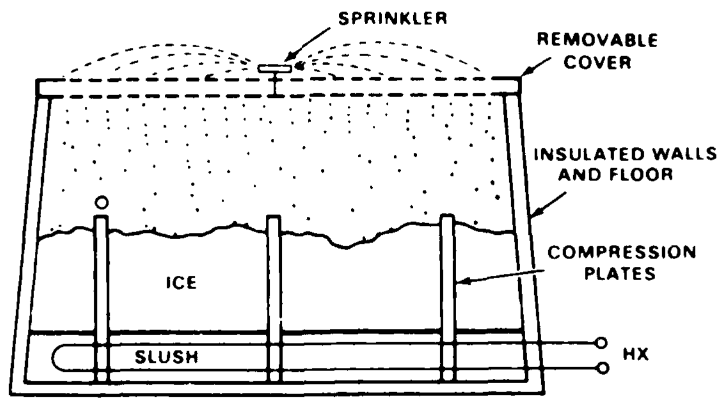


Figure 28. Life-cycle costs for heating, cooling, and hot water/25 years.

A few ACES installations have been built, usually sponsored by a utility or the Federal government. Probably the largest is at a Veterans Administration Nursing Home, in Wilmington, DE. The building covers 29,000 sq ft, and the concrete storage bin has a volumetric capacity of 16,000 cu ft. The system can produce 823,000 Btu/hr of heating and 75 tons of cooling. Payback of initial incremental costs from savings in purchased energy is estimated to be 11 years. Off-peak power rates that reduce the payback period are not available for the Wilmington area.

Another annual ice storage concept involves the natural formation of ice during the winter [26]. The ice is stored and used the following summer for any cooling application such as air condtioning. Figure 29 shows one such scheme and alludes to variations. Several development efforts related to this concept are under way in the United States and Canada [75].

The Prudential Insurance Co. recently built a new building in Princeton, NJ, that uses natural ice generated in the winter for air conditioning. The ice generator and storage system is conceptually similar to the one shown in Figure 29 except that a pond is used for storage. Snow-making machines are used to make the ice. The ice system is designed to supply 170,000 ton-hours of cooling, which is the building's required average annual cooling load. A small prototype of the ice generation and storage system was built and tested prior to designing the full-scale installation; however, details of the design and operation of this system are unknown.



DESIGN VARIATIONS – SNOW–MAKING SPRINKLER, BRINE TANK, HEAT PIPE, FLOODED TRAY OR BIN, LAKE HARVESTED

Figure 29. Seasonal energy storage using ice.

4 BUILDING APPLICATIONS OF ENERGY STORAGE

Energy storage may be applied in a wide variety of ways. Generally, these applications will fall under one of the following three categories:

1. Storage for electric load management

2. Storage for energy conservation

3. Storage to increase the equipment capacity.

Energy Storage for Electric Load Management

A hypothetical large typical utility illustrates the reason for electric load management. This utility may generate its baseload with large, modern, high-efficiency coal or nuclear units. Fifty percent of the utility's load may be generated with these units. The broad daily peaks in demand (30 to 40 percent of the load) may be generated with less efficient and older fossil fuel plants. Finally, the peak demand (10 to 20 percent of the load) may be met with oil- or gas-fired steam plants, hydroelectric power, gas- or oil-fired turbines, and diesel generators. Peaking units use expensive fuels, generally have lower efficiencies, and are used only intermittently. Electricity generated with base load plants is much cheaper than that generated by load following and peaking plants. For larger users of electricity, this electric generation mix is reflected in the rate structure in two basic ways. First, there is a time-of-use rate, which means that the kilowatt-hours of electricity purchased during the peak times (daytime) cost more than those purchased during off-peak times (night). Second, the utility may add a demand charge that is based on the user's monthly peak electrical demand (kW). The rate structure for large users of electricity may be complex. It may be based on both time-of-use and peak electric demand. The time-of-use may have one or more intermediate periods; both the time-of-use and demand charges may be seasonally adjusted. The demand charge may apply only during the month that it is experienced, or it may extend for several months. Thermal energy storage for electric load management implies the use of electricity at night to generate heat or cold that will be stored for use the following day. For example, chillers may be operated at night to generate cold water or ice. The stored cold can then be used the following day for air conditioning. The economic result is two-fold. First, electricity is purchased more cheaply, and second, the chiller electric demand is moved to the nighttime valley and no longer contributes the peak that must be met by the utility to daytime. Although the purpose of energy storage for electric load management is primarily economic (cheaper electricity), it may also conserve scarce fuels, in that the electric requirements are met with efficient coal and nuclear plants instead of gas- and oil-fired units; also, the chiller efficiency would be greater at night.

Most military bases have a single electric meter that records the electricity (kWh) and peak electric demand (kW) for the entire base. For cold storage to accomplish its goal of reducing overall peak electric load demand, the peak demand for the air-conditioning system that is being considered for storage must coincide reasonably well with that of the entire base.

There may be only limited heat storage applications for the purpose of load management in the Army. This is because natural gas and oil are the preferred fuels for heating buildings; the rate structure for these fuels normally does not contain significant time-of-use or demand components. Although some Army buildings are heated with

resistance heat, these are being phased out. There may be situations where, because of special considerations, resistance heat is preferred, so heat storage for electric load management may be considered. For example, as noted earlier in the description of "concrete heat storage," the entire electric heating system can be external to the building envelope, with no penetrations for duct work or piping; thus, it may be ideal for heating explosion-prone spaces.

Cool storage for electric load management has considerable application to large Army buildings or central chillers. Figure 30 depicts, qualitatively, the two strategies commonly considered for this application. The top illustration shows a conventional chiller without storage. The load diagram shows the diurnal demand profile (kW) drawn by the chiller. The middle diagram depicts the "full-storage" option, in which all the cold that the building requires is generated during off-peak hours. The following day, the chiller is shut down, and all of the building's air-conditioning requirements are met from

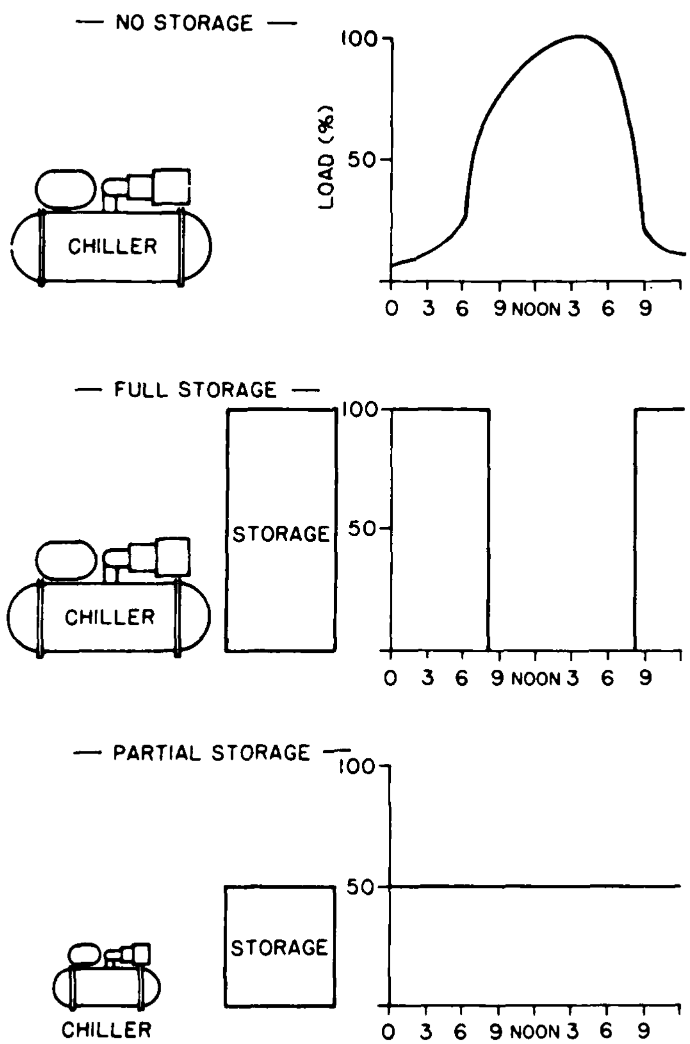


Figure 30. Operating strategies for cold storage systems.

storage. The chiller is shown to be about the same size as the conventional chiller, and the cold storage tank is large. The bottom diagram illustrates the "partial-storage" or the "storage-assist" option. Here, the chiller is sized to operate continuously (24 hr) on the design day. At night, when the chiller's full output is not required for air conditioning, the excess cold goes into storage. The next day, the chiller is assisted by storage to meet the building's peak air-conditioning requirements. In this diagram, the chiller is shown to be much smaller than a conventional chiller or a chiller in the full storage mode. Also, the storage unit is much smaller than in the full storage mode. Although it involves smaller equipment, it only shifts part of the load. In the case of either operational strategy, storage may be achieved with cold water or ice.

A sample calculation for an administration/classroom building at Fort Hood, TX, is presented to show the principles involved and to address the cost. This building was simulated by the U.S. Army Construction Engineering Research Laboratory (USA-CERL) with the Building Loads Analysis and Systems Thermodynamics (BLAST) system. The building has 14,800 sq ft on one floor and a maximum occupancy of 257 people. The simulation was performed for the "design day" in this geographic region, and it was assumed that the design day occurred during the week. Night setback of the thermostat was not used, and the building was maintained at 78°F for the entire 24-hr period. The building was used heavily from 0830 to 1730 hours. Figure 31 shows the cooling profile supplied by the air conditioner. The peak cooling load could be met with a 26.8-ton air conditioner. The performance of the air conditioner is such that 3.12 Btu/hr of cold is delivered for each Btu/hr of electric input. Therefore, at the daily peak, the air conditioner draws 30.3 kW of electricity.

In the following calculations, several simplifying assumptions are made:

1. The air conditioner's performance does not change with outdoor temperature.

2. Heat gains by the storage unit and associated piping from ambient will be neglected.

The building's total, worst-day cooling requirements are the sum of the hourly cooling loads. Table 13 gives the hourly cooling loads, along with energy flows for the two storage modes. As shown, the total cooling requirement for this worst day is 3.87×10^6 Btu.

For the full-storage mode, it is assumed that the utility off-peak period extends from 2200 hours at night until 0800 hours the next morning, or 10 hours. The capacity of an air conditioner to supply the entire day's load during a 10-hr period will be $3.87 \times 10^6/10 = 3.87 \times 10^5$ Btu/hr, or a 32.3-ton unit. Figure 32 is a replot of the building requirements, with the air conditioner output profile for the full-storage mode superimposed. Note that the capacity of the air conditioner in the full-storage mode is only about 20 percent greater than the theoretical maximum capacity of a conventional air conditioner for this particular building and set of assumptions. Undoubtedly, the air conditioner in any existing building is at least 20 percent larger than theoretical, and usually considerably more than that. Thus, the existing air conditioner may be adequately sized already for the retrofit full-storage application, although certain other modifications may be necessary.

Table 13 shows the energy flows for the full-storage mode. During the off-peak period, the air conditioner is used to cool the building, but most of its output goes into storage. At 0800 hours, the chiller is shut down, and the building draws all its cooling requirements from storage until 2200 hours that night. The sum of the hourly cooling requirements coming from storage will be the storage unit's capacity. Thus, the capacity is 3.19×10^6 Btu.

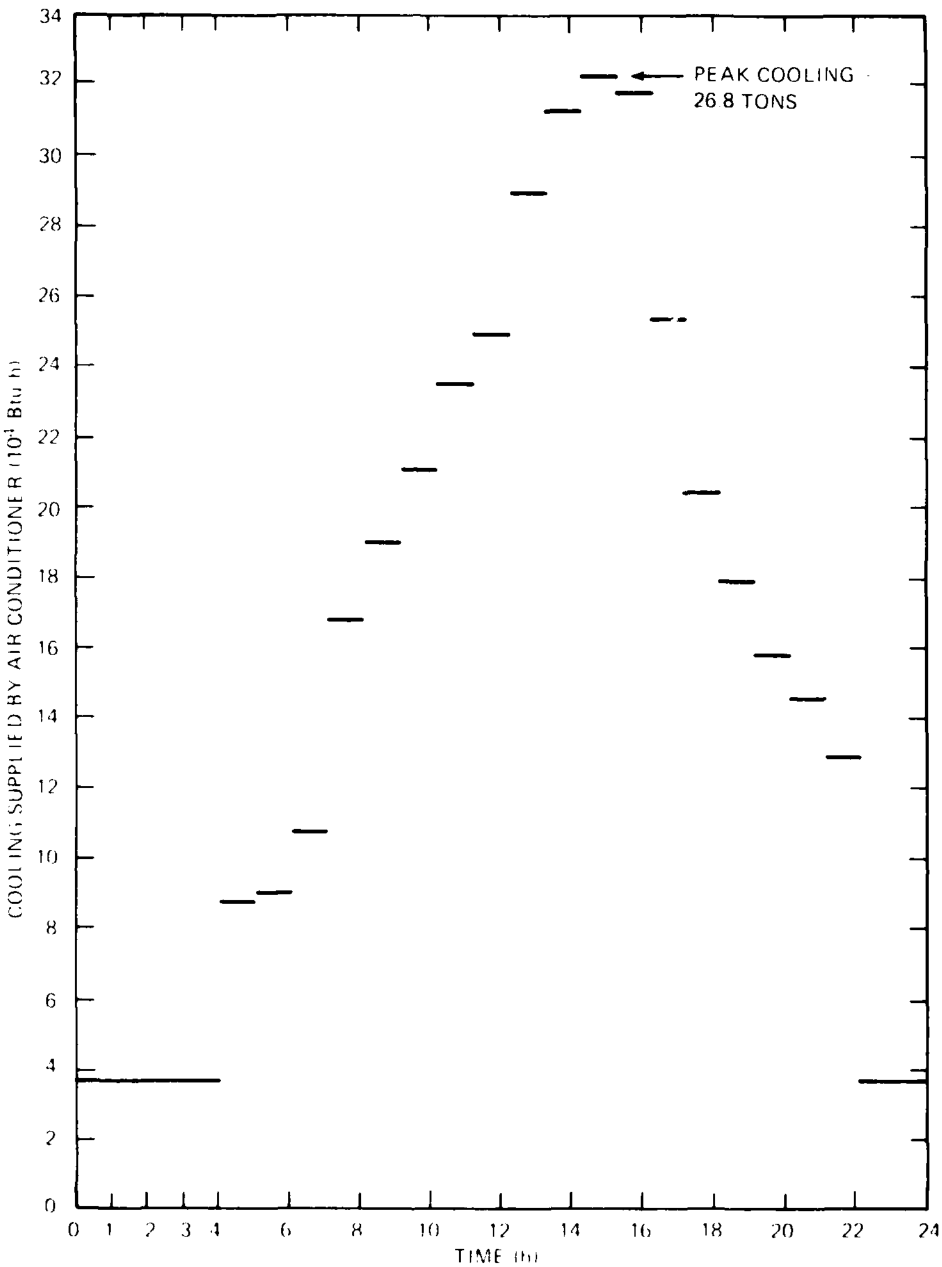


Figure 31. Cooling requirements for an administration building located at Fort Hood, TX.

If cold water is used as the storage medium, the required capacity could be met with a 19,200-gal tank operating with a 20°F ΔT between 35° and 55°F. If ice storage is used, the capacity could be met with a single Chester-Jensen storage unit or with a bank of three Calmac storage modules.

If the partial-storage mode is selected, then the air conditioner is sized to supply the entire worst-day load by operating continuously for 24 hr. In this case, the air conditioner's capacity will be $3.87 \times 10^6/24 = 1.61 \times 10^5$ or 13.4 tons. Figure 32 shows the air

Table 13

Energy Flows to Air Condition Administration Building

Time (hrs)	Cooling* Required by Building (10^4 Btu/hr)	Full Storage (10-Hr Charge): A/C Output (10^4 Btu/hr)	Full Storage: A/C Output To Building (10^4 Btu/hr)	Full Storage: A/C Output To Storage (10^4 Btu/hr)	Full Storage: Storage Output To Building (10^4 Btu/hr)	Partial Storage: A/C Output (10^4 Btu/hr)	Partial Storage: A/C Output To Building (10^4 Btu/hr)	Partial Storage: A/C Output To Storage (10^4 Btu/hr)	Partial Storage: Storage Output to Building (10^4 Btu/hr)
0-1	3.74	38.7	3.7	34.9	0.0	16.12	3.7	12.4	0.0
2	3.74	38.7	3.7	34.9	0.0	16.12	3.7	12.4	0.0
3	3.74	38.7	3.7	34.9	0.0	16.12	3.7	12.4	0.0
4	3.74	38.7	3.7	34.9	0.0	16.12	3.7	12.4	0.0
5	8.86	38.7	8.9	29.8	0.0	16.12	8.9	7.3	0.0
6	9.05	38.7	9.1	29.7	0.0	16.12	9.1	7.1	0.0
7	10.78	38.7	10.8	27.9	0.0	16.12	10.8	5.3	0.0
8	16.80	38.7	16.8	21.9	0.0	16.12	16.12	0.0	0.7
9	18.99				19.0	16.12	16.12	0.0	2.9
10	21.05				21.0	16.12	16.12	0.0	4.9
11	23.51				23.5	16.12	16.12	0.0	7.4
12	24.91				24.9	16.12	16.12	0.0	8.8
13	28.91				28.9	16.12	16.12	0.0	12.8
14	31.23				31.2	16.12	16.12	0.0	15.1
15	32.14	A/C	A/C	A/C	32.1	16.12	16.12	0.0	16.0
16	31.70	Secured	Secured	Secured	31.7	16.12	16.12	0.0	15.6
17	25.25				25.2	16.12	16.12	0.0	9.1
18	20.37				20.4	16.12	16.12	0.0	4.2
19	17.88				17.9	16.12	16.12	0.0	1.8
20	15.81				15.8	16.12	15.8	0.3	0.0
21	14.55				14.6	16.12	14.6	1.6	0.0
22	12.78				12.8	16.12	12.8	3.3	0.0
23	3.73	38.7	3.7	35.1	0.0	16.12	3.7	12.4	0.0
24	3.73	38.7	3.7	35.0	0.0	16.12	3.7	12.4	0.0
Sum =	386.99	387.0	67.9	319.0	319.0	386.9	287.6	99.3	99.3

*Equal to cooling supplied by air conditioning when operated in the conventional mode.

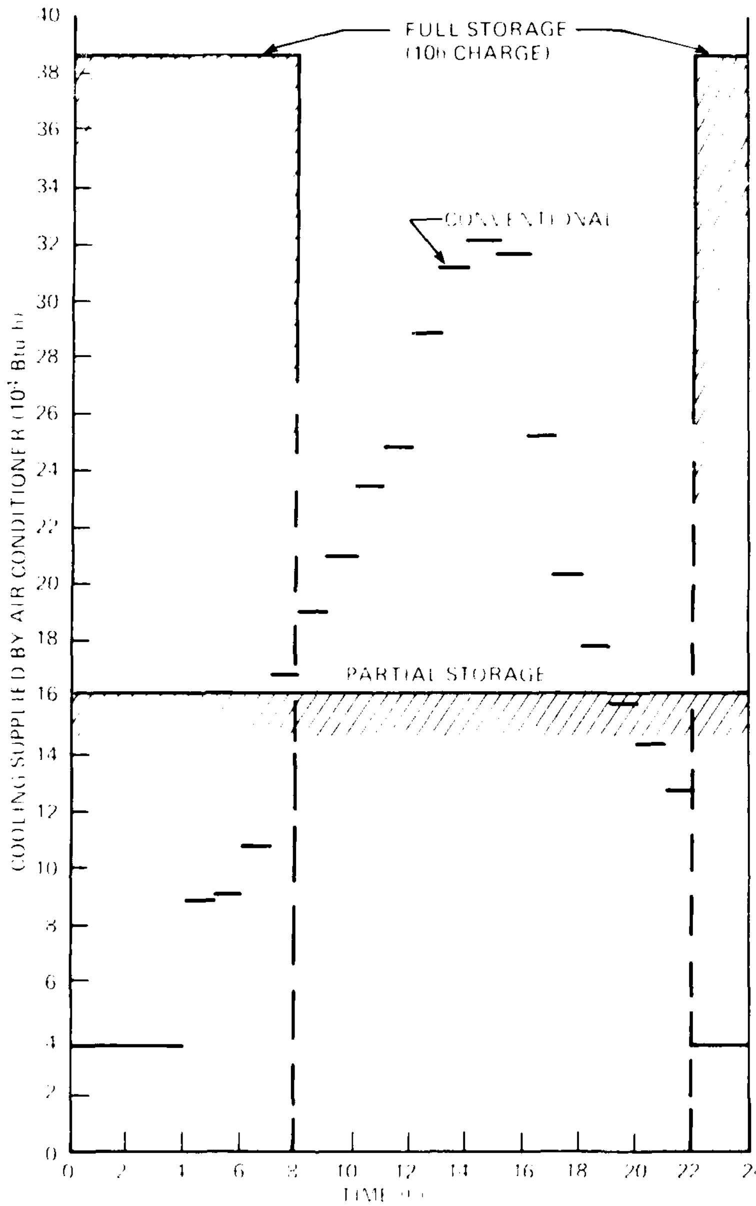


Figure 32. Cooling supplied to administration building (Fort Hood, TX) showing different modes of operation.

conditioner to be operating continuously in this capacity, and Table 13 shows the energy flows for this operating mode. During the night, excess cool generated by the air conditioner is stored. The next day, the air conditioner's output is enhanced by the storage unit to meet building requirements. In this example, the worst hour is between 1400 and 1500 hours. At this time, the output from storage is about equal to the air conditioner's capacity. Again, the sum of the hourly cooling requirements from storage will be the storage system's capacity (in this case 99.3 x 10^4 Btu).

If cold water is used as the storage medium, the required capacity could be met with a 6000-gal tank operating with a 20°F ΔT between 35° and 55°F. If ice storage is used, the capacity could be met with a single storage unit from either Chester-Jensen or Calmac.

Table 14 summarizes the design parameters for the Fort Hood Administration Building. These parameters are a strong function of the building involved and its daily load profile, which reflects its use characteristics, the climatic region in which it is located, and the utility rate structure. For this particular building, and assuming a 10-hr off-peak period, it is observed that the air conditioner's capacity for the partial-storage mode is less than half the size required for the full-storage mode. Also, the storage system capacity for the partial-storage mode is less than one third the capacity required for full-storage mode. Thus, consider a building with the characteristics of the one analyzed here and equipped with a full-storage air-conditioning installation. A second building with roughly similar characteristics may be built next to the original, and the cooling system will have enough capacity to cool both buildings if the chiller/storage system is repiped to operate in the partial-storage mode. This observation may be of interest to the military because it can be used as a tool for increased preparedness.

Table 14

Summary of Air-Conditioning Operating Modes for Administration Building at Fort Hood, TX

	Conventional	Full Storage	Partial Storage
A/C capacity (tons)	26.8	32.2	13.4
A/C electrical demand (kW)			
High during peak hours	30.2	0.0	15.2
Low during off-peak hours	3.5	36.4	15.2
Reduction in peak demand during peak period from conventional (kW)		30.2	15.0
Storage system capacity (Btu)		3.19×10^6	0.99×10^6
Chiller (Btu/hr)	32.1×10^4		16.1×10^4
Storage (Btu/hr)		32.1×10^4	16.0×10^4
Installed chiller cost	$16,100	$18,200	$11,000
Installed cold water storage cost		$13,200	$ 4,600
Total system cost	$16,100	$31,400	$15,600
Reduction in demand charge from conventional system for design month, assuming $6/kW		$181	$90
Approximate savings in electricity cost, assuming 2¢/kWh differential in TOU* rates		$190/mo	$55/mo

*Time of use.

Table 14 also includes new construction costs for each system. These numbers were estimated from cost correlations presented in Asbury, et al. [40]. Cold water is the assumed storage medium. In sizing the tanks, it was assumed that the working range of the water was 40° to 60°F, thus having an effective ΔT of 20°F. Cast-in-place concrete tanks were assumed for cold water storage.

The total system cost of a partial-storage installation is almost the same as for a conventional system, while the full-storage system costs about twice as much. The energy savings result from two factors. First, there is the reduction in demand charge, which was assumed to be a flat \$6/kW with no complicating factors such as seasonal adjustments and ratchet effects. The savings in demand charges are for the month that includes the design day for which the building was simulated. The reduction in demand charges would be less for the other summer months. The other energy cost savings result from a differential in the time-of-use rate. It was assumed that off-peak electricity costs 2¢/kWh less than on-peak electricity, and that the off-peak extends from 2200 to 0800 hours (10 hr). Again, the building simulation was only for 1 day, so the savings for that day were multiplied by 30.5 to estimate the monthly savings. Thus, these savings would be expected to be the maximum savings. Furthermore, they would be expected to be less for the other summer months. With all these uncertainties, the calculation is extended one step further. For a large building in a southern climate, the air-conditioning season may be 8 months long. It is assumed that both savings per month listed in Table 14 for the full-storage system can be multiplied by 6 months to give a "reasonable" estimate of the annual savings. Thus, the annual savings resulting from the cost of electricity and reduction in demand taken together will be (181 + 190)(6) = \$2226. The simple payback for the incremental cost of installing a full-storage system will be (31,400-16,100)/2226 = 6.9 years. The savings are a strong function of the utility rate structure, and these vary considerably across the nation. If either the cost of electricity or the reduction in demand is considered individually, then the simple payback period would be about 14 years.

The estimated cost of the partial-storage system is slightly less than that for the conventional system. Also, the monthly electricity savings for the warmest month would be about \$145. The annual electrical savings, estimated as above, would be about (6)(145) = \$870.

Figure 33 and Table 15 give the results of a calculation for the same type of administration building, but at Fort Dix, NJ. This simulation was performed for a "design day" in Philadelphia, PA. The outdoor dry-bulb temperature in Philadelphia on the design day peaked at 90°F. (At Fort Hood, it peaked at 97°F.) The administration building performance characteristics, internal load profile, and utility off-peak time schedule were assumed to be the same for both Fort Hood and Fort Dix. Thus the results of sizing calculations reported in Table 15 for Fort Dix are similar to those reported in Table 14 for Fort Hood, but decreased in magnitude to reflect the cooler climate.

Figure 34 and Table 16 give the results of a calculation for a "rolling pin" type barracks at Fort Hood. Cooling requirements for this barracks peaks in the early evening, and also remain fairly high all night. This reflects the high nighttime occupancy and low daytime occupancy of the building. As a result, the ratio of air-conditioner capacity for full storage to conventional air-conditioner capacity is greater than the same ratio for the administration building whose occupancy schedule is reversed.

Hourly electrical consumption data for August was obtained for a central cooling plant at Fort Hood, TX, which supplies cold water for air conditioning several barracks.

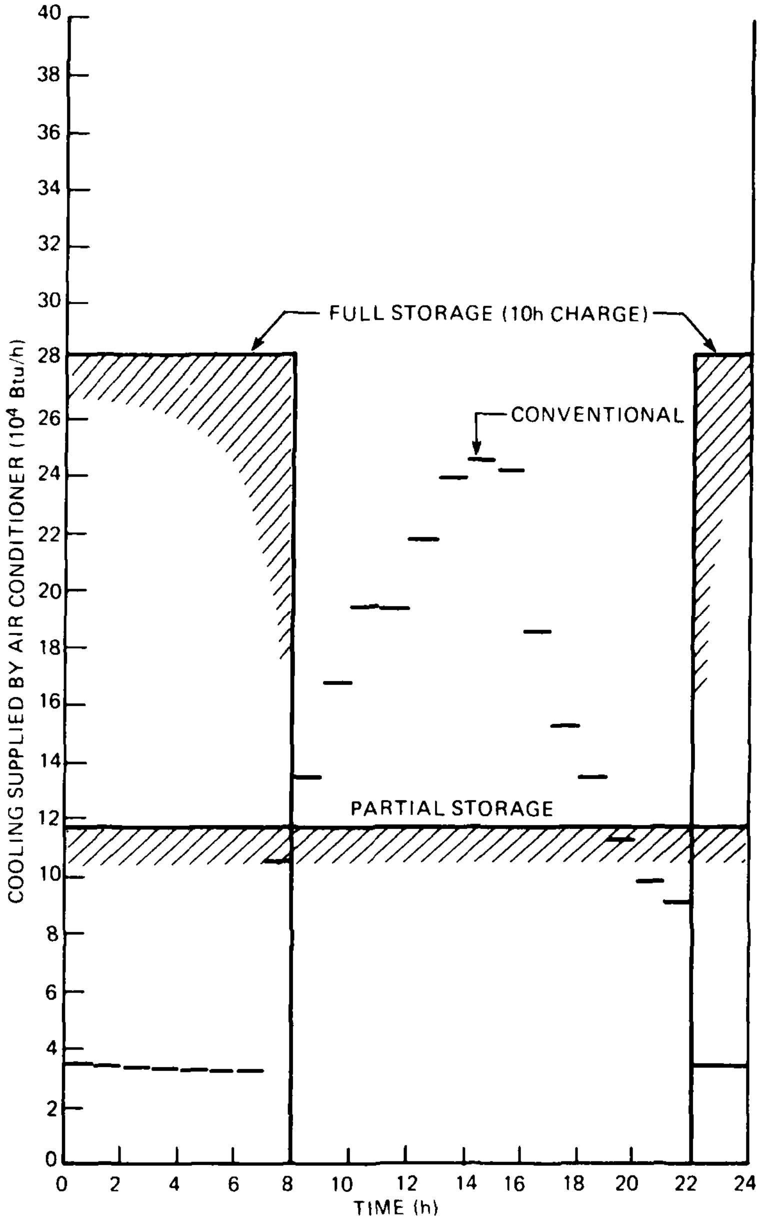


Figure 33. Cooling supplied to administration building (Fort Dix, NJ) showing different modes of operation.

The worst day during this period, in terms of cooling requirements, occurred on August 23. Figure 35 gives the hourly profile of cooling water requirements, assuming a COP of 3.0. As is typical for barracks, the profile is fairly flat and peaks during the evening hours. The partial-storage mode would probably not be appropriate for this application. However, the full-storage mode might be.

Table 17 shows results of the analysis. Costs were determined for two cases: a new installation and a retrofit. In the case of the retrofit, the purchased chiller need only be of sufficient capacity to make up the difference in capacity between the existing chiller and that required for the full-storage mode. Estimating the simple payback period of the full-storage mode over a conventional system (employing the same approximate method used earlier, which takes credit for both the reduction in demand and

Table 15

Summary of Air-Conditioning Operating Modes for Administration Building at Fort Dix, NJ

	Conventional	Full Storage	Partial Storage
A/C capacity (tons)	20.5	23.6	9.8
A/C electrical demand (kW)			
High during peak hours	23.2	0.0	11.1
Low during off-peak hours	3.0	26.6	11.1
Reduction in peak demand during peak period from conventional (kW)		23.2	12.1
Storage system capacity (Btu)		2.42×10^6	0.81×10^6
Building peak demand supplied by			
Chiller (Btu/hr)	24.7×10^4		11.8×10^4
Storage (Btu/hr)		24.7×10^4	12.9×10^4
Installed chiller cost	$13,700	$15,300	$ 8,800
Installed cold water storage cost		$10,400	$ 3,900
Total system cost	$13,700	$25,700	$12,700
Reduction in demand charge from conventional system for design month, assuming $6/kW		$139	$72
Approximate savings in electricity cost, assuming 2¢/kWh differential in TOU rates		$144	$45

electricity cost) gives 6.5 years for the new installation and 4.9 years for the retrofit. The same caveat applies here as previously. The payback period may be much greater or much less, depending on the rate structure of the utility involved.

Argonne National Laboratory has recently assessed cold storage applications in commercial buildings for electric load management purposes [40]. The cost of installing and operating cold storage systems was estimated for four buildings and compared to conventional air conditioning; both new construction and retrofits were considered. Building characteristics were as follows:

1. Building A: Seven-story masonry office building containing about 650,000 sq ft of floor space. The HVAC system operates from 0600 to 1700 hours.

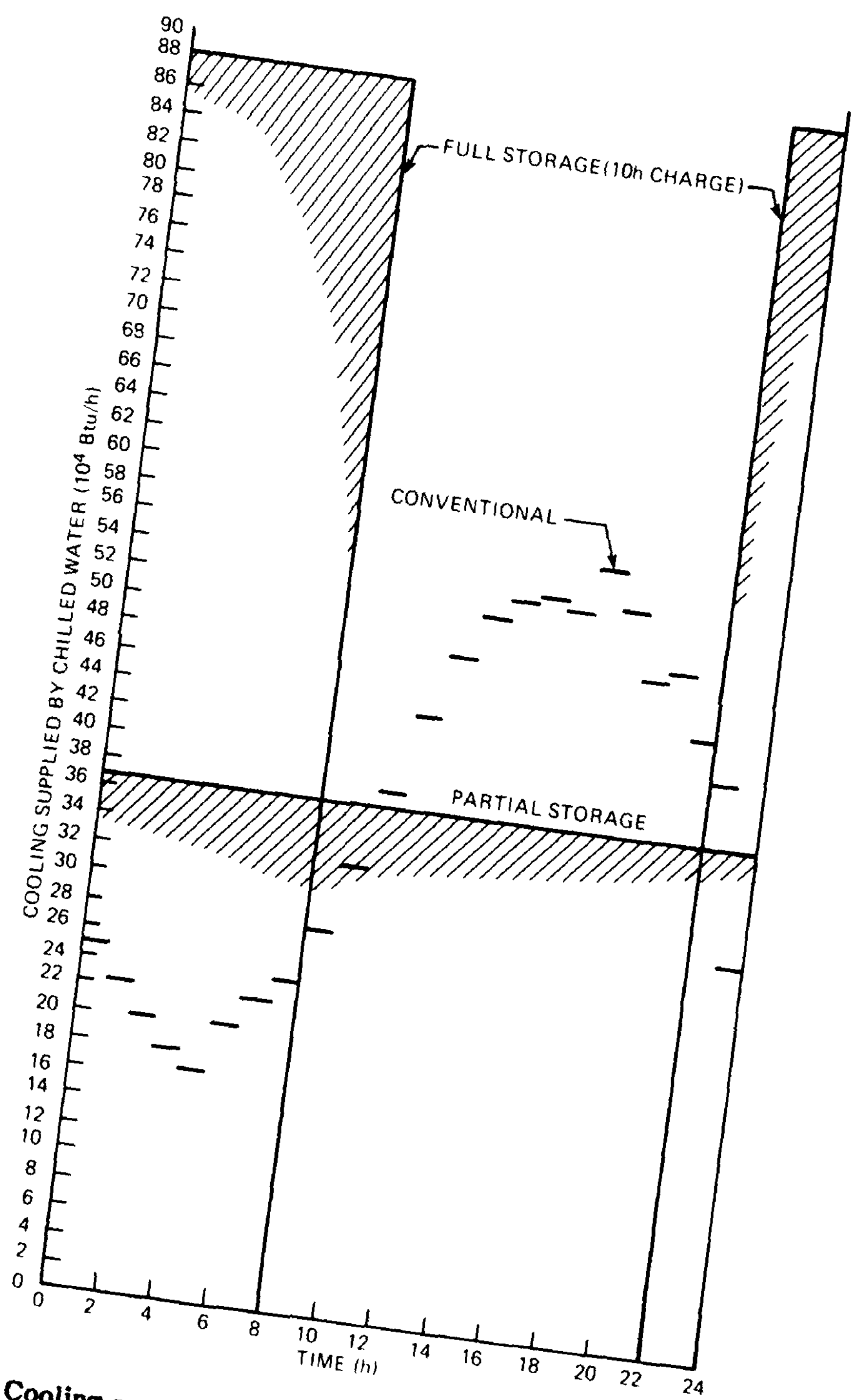


Figure 34. **Cooling supplied to rolling pin barracks (Fort Hood, TX) showing different modes of operation.**

Table 16

Summary of Air-Conditioning Operating Modes for Rolling Pin Type Barracks at Fort Hood, TX

	Conventional	Full Storage	Partial Storage
A/C capacity (tons)	44.0	73.6	30.7
A/C electrical demand (kW)			
High during peak hours	49.6	0.0	34.6
Low during off-peak hours	15.3	83.1	34.6
Reduction in peak demand during peak period from conventional (kW)		49.6	15.0
Storage system capacity (Btu)		6.5×10^6	1.5×10^6
Building peak demand supplied by			
Chiller (Btu/hr)	55.5×10^4		36.8×10^4
Storage (Btu/hr)		55.5×50^4	18.7×10^4
Installed chiller cost	$21,600	$30,500	$17,800
Installed cold water storage cost		$24,900	$ 6,600
Total system cost	$21,600	$55,400	$24,400
Reduction in demand charge from conventional system for design month, assuming $6/kWh		$298	$90
Approximate savings in electricity cost, assuming 2¢/kWh differential in TOU rates		$386	$79

2. Building B: Eight-story steel and glass office building containing 250,000 sq ft of floor space. The HVAC system operates from 0600 to 1800 hours.

3. Building C: Four-story concrete office building containing 115,000 sq ft of floor space. The HVAC system operates from 0700 to 1900 hours.

4. Building D: Two-story shopping mall containing 750,000 sq ft of floor space. The HVAC system operates from 0700 to 2100 hours.

For buildings A and B, actual building electric profiles that were measured every 15 minutes were used for the analysis. Buildings C and D were simulated on DOE-2--a Department of Energy computer code similar to BLAST. Buildings A and B are located in the middle Atlantic service area, and buildings C and D in the midwestern service area.

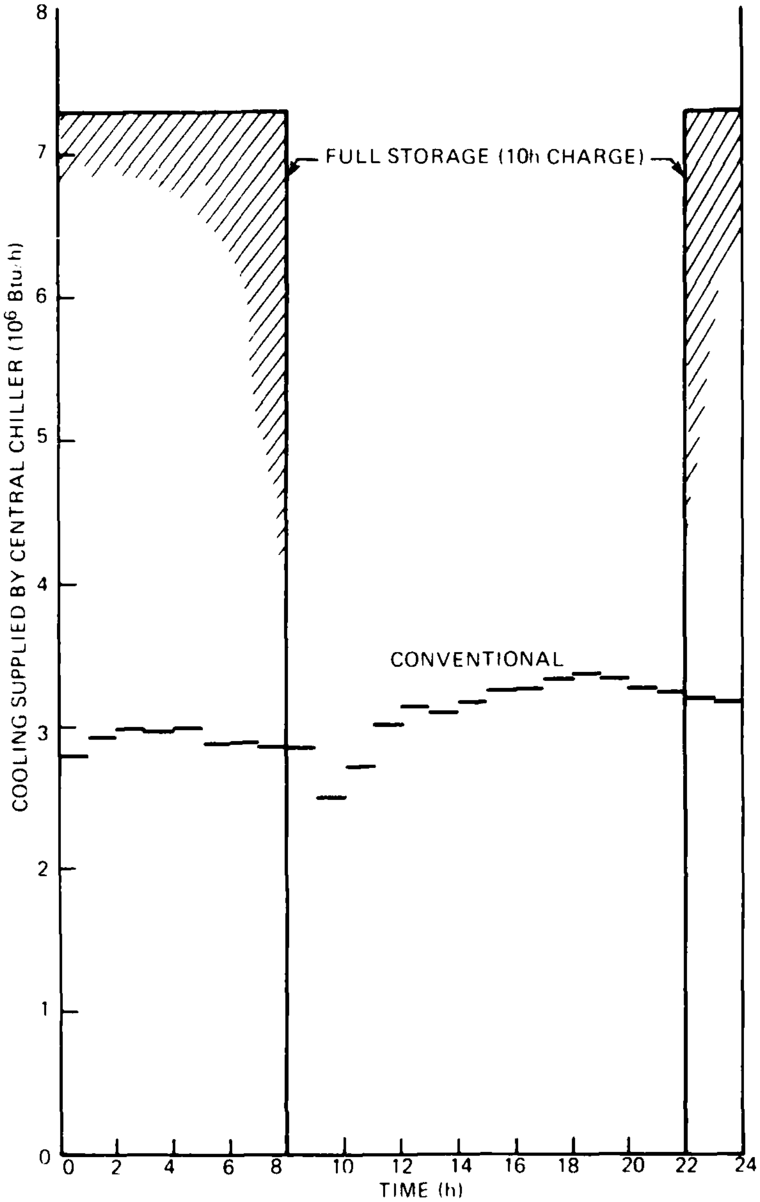


Figure 35. Cooling supplied by central chiller plant to barracks (Fort Hood, TX) showing different modes of operation.

Full-storage and partial-storage, both as cold water and ice, were assessed. Both utilities had complex rate structures for large customers. The time-of-use rate is fairly straightforward and amounts to a difference between on-peak and off-peak rates of 1¢/kWh. The demand charge is complex and includes a ratchet. Each kilowatt reduction in on-peak demand can reduce the annual bill by $76 for the middle Atlantic service area, and $55 for the midwestern service area. Monthly savings resulting from shifting the electric load to off-peak periods and from reduction in the peak period demand were computed. Annual savings resulting from the use of storage compared to a conventional system were computed and the payback period determined. Table 18 provides the results of these calculations.

Table 17

Summary of Operating Modes for Control Chiller of Fort Hood, TX

	Conventional	Full Storage
A/C capacity (tons)	280	608
A/C electrical demand (kW)	328	0
High during on-peak period	273	713
Low during off-peak period		328
Reduction in peak demand from conventional (kW)		
Storage system capacity (Btu)		73×10^6
(gallons)	2.9×10^5	

	New	New	Retrofit
Purchased chiller size (tons)	280	608	328
Installed chiller cost	$73,000	$125,000	$82,000
Installed cold meter storage cost		$126,000	$126,000
Total system	$73,000	$251,000	$208,000
Reduction in demand charge from conventional system for design month, assuming $6/kW		$1970/month	$1970/month
Approximate savings in electricity cost, assuming 2¢/kWh differential in TOU rates		$2590/month	$2590/month

Conclusions of this study were [40]:

1. Cool storage is an effective load management technology for reducing commercial-building peak demands.

2. Chilled-water systems consume less energy than ice-building systems and may actually consume less than conventional cooling systems (that is, cooler nighttime condenser temperatures can more than offset storage losses and other burdens).

3. Partial-storage systems, because of their smaller compressor capacity requirements, involve much lower capital outlays than full-storage systems; partial storage also offers faster payback than full storage.

4. For the storage costs used in this analysis, chilled-water storage offers a faster payback than ice systems in new applications. Ice-building systems may have cost and space advantages in retrofit applications.

5. Storage is more economical in buildings with short daily occupancy periods and narrow cooling loads than in buildings with longer occupancy periods.

6. Storage is more effective in service areas having large on-peak demand charges combined with long ratchets.

Table 18

Results of Economic Assessment of Cold Storage in Four Buildings

System	Bill Savings ($\$10^3$)	Incremental investemt ($\$10^3$) New	Incremental investemt ($\$10^3$) Retrofit	Payback (year) New	Payback (year) Retrofit
		Building A			
Chilled water					
Partial storage	52.6	160.7	292.8	3.1	5.6
Full storage	102.9	331.9	513.7	3.2	5.0
Ice building					
Partial storage	34.3	152.1	152.1	4.4	4.4
Full storage	89.1	380.4	380.4	4.3	4.3
		Building B			
Chilled water					
Partial storage	34.4	89.6	176.3	2.6	5.1
Full storage	63.1	248.4	383.9	3.9	6.1
Ice building					
Partial storage	23.7	112.0	112.0	4.7	4.7
Full storage	52.4	329.2	329.2	6.3	6.3
		Building C			
Chilled water					
Partial storage	4.6	57.8	111.9	12.6	24.3
Full storage	12.8	233.9	337.0	18.3	26.3
Ice building					
Partial storage	3.0	83.2	83.2	27.8	27.8
Full storage	10.2	324.6	324.6	31.8	31.8
		Building D			
Chilled water					
Partial storage	44.9	123.7	374.4	2.8	8.3
Full storage	88.8	1409.9	1985.5	15.6	22.4
Ice building					
Partial storage	31.7	118.1	118.1	3.7	3.7
Full storage	68.6	1213.0	1213.0	17.7	17.7

Energy Storage for Conservation

Energy storage for conservation implies the capture and storage of energy (either hot or cold) such that it will replace the dedicated use of fuel during some subsequent time for the heating or cooling application. The source may be energy that is currently wasted, or it may be environmental in nature. Conventional solar energy on a diurnal cycle is not included in this discussion. Environmental energy in the context of this report implies seasonal energy storage (for example, the capture and storage of winter chill for air conditioning the following summer). For conservation applications, storage almost universally involves thermal energy storage. Many excellent conservation

measures involve no storage at all; rather, heat is recovered and used directly. Table 19 lists energy sources, storage parameters, and applications that may be found on a military post. This list is not exhaustive and is intended to give examples only.

Waste Heat From Air Conditioners and Chillers

An air-conditioner compressor discharges superheated refrigerant vapor. In recent years, recovery of this heat for some other application has been gaining wide acceptance in the United States. The energy recovery is a two-stage process. First, there is the heat recoverable from desuperheating the refrigerant vapor, and second, there is the heat of condensation. For residential and small commercial air conditioners, practical considerations dictate that only the superheat energy may be recovered. Typically, this amounts to 2000 to 3000 Btu/hr per ton of capacity. Many companies manufacture retrofit recovery units for this application. They are primarily targeted toward the residential market. They are designed so that the waterflows countercurrent to the superheated freon, thus, temperatures exceeding 140°F are attainable, and this is adequate for domestic applications. Large air conditioners are designed to recover all the waste heat. For example, the Trane Company manufactures a complete line of centrifugal and reciprocating air conditioners with capacities up to 1630 tons and with heat recovery. Typically, these units recover 14,000 to 17,000 Btu/hr per ton of capacity at design conditions. The recovery water temperature is as high as 105°F for centrifugal compressors and 125°F for reciprocating compressors.

Applications of waste heat recovered as hot water from air conditioning would be numerous on an Army post, including:

1. Domestic hot water in a barracks

2. Hot water for cooking, washing, and cleaning at a dining facility

3. Hot water for post laundry facilities.

It would be necessary to estimate the economics of each application separately. However, based on the wide acceptance of heat-recovery air conditioners in the private sector, the economics of many applications would undoubtedly be favorable.

Waste Heat From Effluent Flows

There are probably many high-temperature effluent flows of both water and air from the various facilities on an Army post. Table 19 lists many of these and suggests storage options and applications. One example is reported in a study [44] on the use of waste heat from an Army propellant forced air drying house at Dover, NJ. Because this technology area is extremely diverse, both in terms of energy sources and the application of recovered energy, the economics of waste heat recovery, storage, and use must be considered on a case-by-case basis. A specific waste heat use concept may be economically attractive for one Army post, but not another, for a variety of reasons. Because of this heterogeneity, it is very hard to make generic conclusions in this area.

Many studies have been conducted on the use of waste heat [41,43,44,45,46,47]. Most of these are concerned with waste heat recovery from industrial processes. However, some relate to commercial processes that are probably more equivalent to the usual facilities on an Army post. Often, the waste heat use concept does not include storage. An example of a military facility that would not involve storage or only minimal storage would be a central laundry equipped with its own boiler. The time

Table 19

Possible Energy Sources, Storage, and Applications on an Army Post

Energy Source	Storage	Cycle	Possible Applications
Waste heat from chillers and air conditioners	Hot water	Diurnal	Domestic use in building(s) served by chiller. Preheating boiler feedwater.
Waste heat from central laundries			
Hot water	None or hot water	Heat exchanger	Preheating incoming water.
Hot humid air	None	Heat exchanger	Preheating incoming air.
Waste heat from dining facilities			
Hot water	Hot water	Diurnal	Washing and cleaning.
Cooking exhaust	Hot water	Diurnal	Washing and cleaning.
Waste heat from barracks showers and laundries	None	Heat exchanger	Preheating incoming water.
Waste heat from incinerators	Hot water	Diurnal	Building heating and domestic uses.
	Hot water in aquifers or ponds	Annual	District heating.
Cogeneration facility	Hot water	Diurnal	Building heating and domestic uses.
Heat recovery from engines	Hot water	Diurnal	Remote stations, heating, or domestic uses.
Winter chill	Cold water in aquifers or ice in ponds	Annual	District cooling.
Summer heat	Hot water in aquifers or ponds	Annual	District heating.
Waste heat from maintenance facilities	Hot water or other	Diurnal	Washing, preheating, space heating, other.

coincidence of the boiler feed water flow rate and the hot effluent discharge would be about the same. Thus, the effluent could be used to preheat the boiler feed water without storage or with just a small amount of storage. Similarly, the hot, humid discharge from the laundry dryers could be used to preheat incoming air without storage.

Figure 36 shows a generic example of waste heat recovery and use, both with and without storage. In this example, a dedicated boiler supplies hot water of 140°F to an undefined application, which could be a central laundry. The flow rate is taken to be 100 gpm for 4 hr each day, 5 days per week, and 50 weeks per year. Hot water effluent from the application is assumed to be 135°F. Without heat recovery, the boiler heats fresh water at 60°F to the required temperature of 140°F, and after being used in the application, it is dumped to the drain at 135°F. A countercurrent heat exchanger is added to the drain that heats fresh water from 60° to 105°F. In Case A, it is assumed that this warm water will be used as feed water to the boiler, and no storage will be involved. In Case B, it is assumed that this water will be used for some application that requires shorage. The figure shows other physical parameters assumed, such as boiler efficiency and overall heat transfer coefficient.

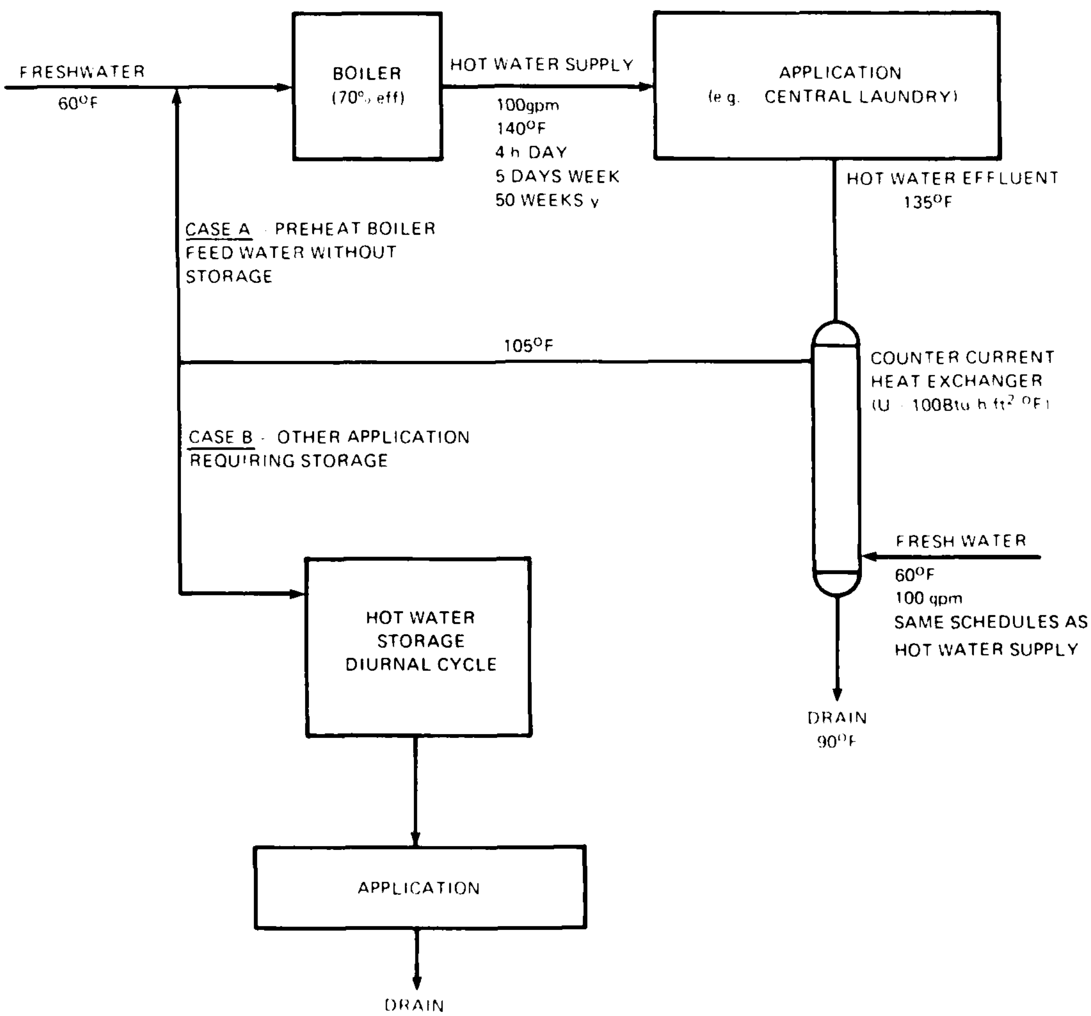


Figure 36. Example of waste heat recovery with and without storage.

Assuming that the cost of gas for the boiler is $4.50/10^6 Btu, the annual cost of gas to heat fresh water to the specified temperature, flow rate, and schedule is $25,700. The annual cost of gas to heat preheated water to the same specified conditions is $11,300. Thus, the annual savings for gas would be about $14,400. The cost of a carbon steel, countercurrent heat exchanger is about $8500 [48]. It is assumed that the installed cost is double the purchase cost, or $17,000. Thus, the simple payback period for this heat-recovery system without storage is 17,000/14,400 or 1.2 years.

For the diurnal cycle, the storage tank would require a capacity of 24,000 gal. The installed cost for a cast-in-place concrete storage tank of this capacity would be $14,400 [40]. Thus, the simple payback period for this waste heat recovery system with storage is (17,000 + 14,400)/14,400 or 2.2 years.

The above calculations are simple, but they indicate that waste heat recovery, either with or without storage, is economically attractive. In general, these calculations were directed toward retrofit applications. For a new installation, credit could also be taken for the purchase of a smaller boiler.

An application of waste heat recovery that might be of particular interest to the military would be remote stations that generate electricity with a motor generator. Transportation costs to get fuel to these stations is undoubtedly expensive. The waste heat from the motor exhaust could be recovered and stored.

Two technology areas that potentially involve considerable energy conservation and can include either diurnal or annual cycle energy storage are energy recovery from an incinerator burning combustible waste and on-post cogeneration of both electricity and hot water. Considerable progress has been made in each of the areas [40-51]. Recovery of energy from burning combustible waste, along with the recovery of other resources such as aluminum, is an emerging technology. For municipal waste, sophisticated pre-treatment and separation steps are often required to segregate the various materials in the feed stack. Most studies indicate that for municipalities, it will be a relatively long time before recovery of energy and other materials from waste will produce a return [49]. Cogeneration of electricity and steam or hot water is an other existing technology, particularly in the industrial sector. Individual plants in the chemical, petroleum, pulp and paper, textile, and food industries sometimes have their own cogeneration plant [52]. Steam turbines are the most common drivers; however, gas turbine and diesel engines are also found at smaller installations. Steam turbines are generally not competitive with gas turbines or diesel generators in the power range of 5 MW or less.

Oak Ridge National Laboratory is assessing the potential use of small cogeneration equipment in decentralized locations on Navy shore facilities [53]. For this study, small cogeneration includes packaged pre-engineered cogeneration systems with electric generating capacities below about 500 kW. Decentralized applications are uses at individual buildings or building complexes. The specific applications usually involve some storage.

A technology area that involves annual cycle storage is the capture and storage of winter chill or summer heat to be used the next season for air conditioning or heating. Water would be the preferred storage medium, and aquifers or ponds might be an appropriate storage container. One concept involves capturing of winter chill as ice and storing it in a pond as in the Prudential Building described earlier [46].

Energy Storage to Increase Equipment Capacity

Increasing the capacity of heating and cooling equipment is not a common application of energy storage. However, it can be used for this purpose, and there are situations in the commercial sector where it is used very effectively. One example is churches, which are normally empty; however, they have a high summer cooling load with a duration of only a few hours during times when services are held. Rather than install a large air conditioner, they install a small chiller and cold storage system (ice or water). The small chiller can generate cold for storage 24 hr a day, all week. Then, during the relatively short periods of occupancy, the stored cold is used for air conditioning. Pasteurization of milk is another example of when a high cooling load is required for a very short period of time. The use of ice storage units is very common for that industry.

Any heating or cooling equipment that is not already operated continuously at its rated capacity can have its capacity increased by operating it continuously and storing the excess heat or cold. The stored heat or cold can then be used to increase the capacity of the basic equipment.

The air-conditioning system in the Administration Building at Fort Hood, TX, discussed previously is an example. From Table 13, the total cooling requirements for this building on the worst day are 3.87×10^6 Btu. The highest building cooling load was at 1500 hours and was 3.21×10^5 Btu/hr. It is assumed that the chiller capacity was at least 25 percent greater than the peak building cooling load, or 4.01×10^5 Btu/hr. If this chiller operated continuously for 24 hr, it would have generated a total of 9.63×10^6 Btu, or almost 2.5 times the total cold required by the building during this worst day. Therefore, the existing chiller could be used to cool an additional building with similar cooling requirements by adding storage. This technique may have implications for military preparedness. For example, during a national emergency and military expansion, new buildings could be heated and cooled with existing equipment by adding storage.

Michigan State University has a central chilling system that cools three buildings. They are considering cold storage so that proposed new buildings would not require the purchase of new chillers [60].

5 POSTWIDE APPLICATIONS OF ENERGY STORAGE

Army posts use large amounts of electricity for a variety of applications in many different buildings. Data supplied for Fort Carson, CO, from mid-November to mid-December, show a consistent daytime peak electrical demand ranging from 9 to 9.5 MW, and a nighttime valley ranging from 5.5 to 6 MW. The average diurnal swing in electrical demand is about 38 percent of the peak demand. The peak demand of larger posts, particularly in a climate with heavy air-conditioning requirements would be considerably greater. Thus, postwide electric load management by energy storage could be of great economic benefit to the Army. Storage technologies for individual buildings and central chillers were discussed in the section on *Energy Storage From Electric Load Management*. Storage technologies are also available that could be used at the main electric power lines entering the post. This would, in effect, manage the entire post's load as a single unit rather than as individual buildings.

The input and output of the load management system would be electricity. The storage system itself may take a variety of forms. Electricity can be stored in batteries or in superconducting magnets. It can be stored mechanically as compressed air (CAES), pumped hydro, or in a flywheel. Finally, it may be stored as thermal energy. Some of these mechanisms require a converter to change the incoming alternating current to the form of energy that will be stored, and then back to AC for use when needed.

The electric utilities are interested in diurnal storage to level their own generation profiles and thus generate more electricity with their large, efficient base load plants. Because of this interest, the Electric Power Research Institute (EPRI) supported a comprehensive assessment of all the storage technologies mentioned above that could be used for central power station load management [59]. An Army post's daily electric use profile is similar to that of the supplying utility in terms of daily swing, and also in the sense that they are both large, even though the utility demand may be one or two orders of magnitude greater than the post demand. Thus, it is useful to consider the EPRI study here.

Table 20 summarizes the expected technical and cost characteristics of the storage systems. The capital cost of the storage system, in first approximation, is the sum of two terms. The costs, Cp, in \$/kW are for power-related equipment, and the costs, Cs, in \$/kWh are for the storage system. Analyzed in this fashion, the total per unit capital cost (C, in \$/kW) is

$$C = Cp + Cs \cdot T \qquad \text{[Eq 2]}$$

where T is the time, in hours, for which the storage system can deliver energy at its rated power output. The "Economic Plant Size" in Table 20 is the smallest plant size below which the economics are unfavorable.

Other conclusions taken directly from the study and that relate to this report are:

1. Energy storage can play an important role in providing generating capacity for peaking and intermediate electric loads, as long as sufficient economic baseload capacity is available for charging energy storage systems with off-peak energy.

Table 20

Expected Technical and Cost Characteristics of Selected Energy Storage Systems

Characteristics	Near Term				Intermediate Term				Long term
			Thermal		Batteries				
	Hydro Pumped Storage	Compressed Air	Steam	Oil	Lead Acid	Advanced	Flywheel	Hydrogen Storage	Superconducting Magnetic
Commercial availability	Present	Present	Before 1985	Before 1985	Before 1985	1985-2000	1985-2000	1985-2000	Post 2000
Economic plant size, MWh or MW	200-2000 MW	200-2000 MW	50-200 MW	50-200 MW	20-50 MWh	20-50 MWh	10-50 MWh	20-50 MW	Greater than 10,000 MWh
Power related costs,* $/kW	90-160	100-210	150-250	150-250	70-80	60-70	65-75	500-860	50-60
Storage related costs,** $/kWh	2-12	4Q3-	30-70	10-15	65-110	20-60	100-300	6-15	30-140***
Expected life, years	50	20-25	25-30	25-30	5-10	10-20	20-25	10-25	20-30
Efficiency,+ %	70-75	++	65-75	65-75	60-75	70-80	70-85	40-50	70-85
Construction lead time years	8-12	3-12	5-12+++	5-12+++	2-3	2-3	2-3	2-3	8-12

*Constant 1975 dollars; does not include cost of money during construction.

**Could be considerably higher.

***These numbers are very preliminary.

+Electric energy out to electric energy in, in percent.

++Heat rate of 4200-5000 Btu/kWh and compressed air pumping requirements from 0.58 to 0.80 kWh (out).

+++Long lead time includes construction of main power plant.

2. A review of a wide range of energy storage concepts has identified technically feasible energy storage technologies that could be commercially available in the near term, intermediate term, and long term.

a. Conventional hydropumped storage is the only proven technology and is now in use.

b. For the near term (through 1985), hydropumped storage with an underground reservoir, compressed air storage, and sensible heat thermal storage integrated with a central power plant appear to be feasible and economical for peaking and intermediate duty.

c. For the intermediate term (1985-2000), advanced batteries, for peaking duty, and advances in the technologies named above appear attractive. Hydrogen storage systems may also be economical for certain immediate-duty applications where large storage capacity is required and where low efficiency (less than 50 percent) and high capital costs are offset by specific system operating and economic benefits.

d. For the long term (beyond 2000), other concepts have potential to become viable storage options. However, the potential of technologies such as superconducting magnetic energy storage cannot be predicted accurately yet.

3. Advanced battery systems appear to be sufficiently compact, economically attractive, and environmentally acceptable to be suitable for dispersed siting throughout utility systems. Continued research and development should be devoted to these systems to seek improvements in battery life and to develop low-cost manufacturing processes.

4. Thermal storage systems, integrated with nuclear plants, are a potentially attractive near-term technology. Further conceptual design work and preliminary engineering studies will be particularly valuable for confirming their potential.

5. Certain technologies were found to be generally unattractive. In particular, flywheel storage systems are too expensive, except for special applications in which high power but little storage capacity is required. Because of their high cost and short life, state-of-the-art lead acid batteries are of interest only where special benefits might be obtained or for small storage capacities. Further study is needed to determine the value of the operating benefits.

6. The evaluation methods used in this study do not provide enough data to determine the optimum amount and type of storage facilities to be installed on any particular electric power system. Each specific application of energy storage requires separate evaluation.

Another study was conducted that may be more appropriate because it concerns storage of electricity by a customer [61]. This study is more specific because the storage system selected was lead-acid batteries. A Bureau of Engraving and Printing facility in Washington, D.C., was selected for several reasons:

1. The facility has peak demands of about 5 to 6 MW in the winter and 8 to 9 MW in the summer. The daily load profile typically shows two short-term spikes of a few hours: one in the morning and one in the afternoon, of about 1 MW. These are quite similar to the daily load profiles of Fort Carson.

2. The electrical demand charges for this facility are about 40 percent of the total bill.

3. Engineering data needed for the study is readily available.

Deep-discharge lead-acid batteries were selected because of their immediate availability and short construction times. The specifications for the storage system determined from this study were:

1. A peak demand of 600 kW for 15 minutes

2. An energy demand of 1.1 MWh over 6 hr discharge.

The utility rate schedule was that proposed for the Washington area. It is complicated and contains both demand charges and time-of-use rates, three daily periods (off peak, intermediate peak, and on peak), and separate rates for the summer and winter months. No ratchet clauses were included. Basically, the rate schedule is as follows:

	Summer Months	**Winter Months**
Energy charge		
On-peak period	0.75¢/kWh	0.39¢/kWh
Intermediate period	0.51¢/kWh	0.33¢/kWh
Off-peak period	0.21¢/kWh	0.21¢/kWh
Demand charge		
On-peak period	\$5.85/kW	\$3.75/kW
Intermediate period	\$3.75/kW	\$2.80/kW
Off-peak period	\$2.80/kW	\$2.80/kW
Rate periods		
On-peak period	12:00 noon to 8:00 p.m.	
Intermediate period	8:00 a.m. to 12:00 noon 8:00 p.m. to 12:00 midnight	
Off-peak period	12:00 midnight to 8:00 a.m.	

Results of this study, which used estimated conventional system costs of \$130/kW for the power processors and \$80/kWh for the lead-acid batteries, indicated a payback period of 9 years. If Department of Energy cost goals for batteries and converters are achieved, the payback period will be reduced to less than 4 years. Furthermore, coupling the battery storage system with a computer-based energy management system capable of shedding and reestablishing interruptible loads will provide a projected payback period of less than 2 years.

6 ENERGY STORAGE TECHNOLOGY ANALYSIS

Table 21 summarizes an assessment of the energy storage technologies appropriate for the Army. Each potential application is described in terms of its energy source, storage mode, and energy use. Not all possible combinations of energy source/storage/use are included. Rather, the table should be considered as representative of the more obvious applications. It is based on:

1. The anticipated cost effectiveness of each storage application

2. The commercial availability of the storage component, auxiliary equipment, and design procedures

3. A judgment on successful solutions to technical problems that may be encountered. Each storage application is also ranked as most attractive, less attractive, or least attractive. Most attractive means that standard equipment and design procedures are generally available today, the cost-effectiveness is expected to be high, and the technical problems that may arise are not expected to be serious. Least attractive means that the storage system is still largely under development or has not been demonstrated yet, the cost-effectiveness is not expected to be good, the technical problems that arise may require sophisticated research and development to resolve, or the storage concept was developed for other highly specific applications. Less attractive falls between these two categories.

From the entries in the "most attractive" section of Table 21, it is apparent that there is considerable potential for money and energy savings if storage is applied to various energy systems. Many of these storage systems (both load management applications and waste heat recovery from chillers) are in fairly common use today, and the equipment and design procedures are readily available. Other storage applications (waste heat recovery from central laundries and internal combustion engines) are anticipated to be straightforward in design, with very few, if any, technical problems, and the cost-effectiveness is expected to be high. The use of storage to increase heating and cooling equipment capacity is also straightforward in design. This particular application may have implications for "military preparedness" in that if a sudden military expansion is necessary, existing heating and cooling equipment can be used to condition additional buildings by adding a storage system. All these energy storage applications are site-specific and must be assessed on a case-by-case basis.

The storage application in which winter chill is captured as ice in a spray pond for air conditioning was placed in the "less attractive" category because of the research and development that would be required before it could be confidently designed. However, the potential for energy conservation resulting from this concept is very high, and the cost-effectiveness is anticipated to be good. Thus, pending successful completion of the required research and development, this application could probably be reclassified as "most attractive."

The use of electric resistance heaters, with refractory bricks as the storage medium is a well-developed technology, and the heaters are commonly available. This technology is classified as "less attractive" only because the Army is phasing out the use of resistance heat.

Table 21

Assessment of Energy Storage Applications for the Army

Application Category	Application: Energy Source	Application: Storage	Application: Energy Use	Comments
		Most Attractive		
Electric load management	Large chillers used during off-peak periods--diurnal cycle	Cold water or ice	Building cooling	Standard equipment commercially available Building must have substantial diurnal swing in cooling requirements Ice storage more compact than cold water storage but possibly less energy efficient.
Conservation	Reject heat from chillers	Hot water in tanks	Domestic purposes	Standard equipment commercially available
Conservation	Waste heat from central laundries			
	Hot water discharge	Hot water in tanks	Preheating boiler feed water	Possible HX fouling from detergents and lint
	Hot air discharge	None	Preheating incoming air	Some direct recycle possible without heat exchange
Conservation	Internal combustion engine exhaust at remote stations	Hot water in tanks	Domestic purposes	Economics may be favorable because of high fuel transportation costs
Increase equipment capacity	Heating and cooling systems	Hot or cold water, or ice	Building heating and cooling	Conservation results from higher efficiencies when operating equipment for longer periods of time at rated capacity Should be regarded as one way to expand equipment capacity and evaluated as the need arises May have "military preparedness" implications

Table 21 (Cont'd)

Application Category	Application: Energy Source	Application: Storage	Application: Energy Use	Comments
		Less Attractive		
Load management and conservation	Annual cycle energy system (ACES)	Ice in tanks (annual cycle)	Building heating and cooling	Economies of scale may improve cost-effectiveness Must be considered as an "advanced" HVAC system
Electric load management	Electrical resistance storage heaters charged during off-peak periods	Refractory bricks	Building heating	Numerous models available from several manufacturers Room sized heaters offer greatest flexibility Army is phasing out resistance heaters for building
Conservation	Winter chill using spray ponds	Ice in tanks (annual cycle)	Air conditioning	Development required for spray ponds High potential for cost-effective conservation
Conservation	Waste heat from dining halls	Hot water in tanks	Cleaning operations	Possible HX fouling from grease and food products
		Least Attractive		
Load management	Postwide electrical service	Batteries, compressed air, or pumped hydro	Electricity for any use	Insufficient industrial experience Probably not cost-efffective
Conservation	Summer heat using solar collectors	Hot water in aquifers or ponds (annual cycle)	Building heating	Probably not cost-effective

Phase change materials other than ice do not appear in the table. Although several commercially available storage systems using phase change materials as the active media are available [59], long-term stability has not generally been demonstrated, particularly with hydrated salts. Some phase change materials such as wax and cross-linked, high-density polyethelene are expected to demonstrate long-term stability; however, they are more expensive than the hydrated salts. They may be of interest for special applications when cost is not the overriding factor.

7 CONCLUSIONS AND RECOMMENDATIONS

Of the numerous energy storage technologies assessed for this study, several were eliminated from further consideration for Army applications because they were found to be cost-ineffective, required components that were not commercially available, or would exhibit technical problems. The remaining technologies were ranked with respect to how responsive they would be to Army needs. The most attractive technologies were found to be those that stored energy emanating from large chillers used during off-peak periods, reject heat from chillers, waste heat from central laundries, exhaust from internal combustion engines, and heating and cooling systems. The least attractive technologies were those that would store energy from installation electrical service and from summer heat. Both were found to be very cost-ineffective.

Of the most favorable technologies, the storage of cold water or ice on a diurnal cycle for electrical load management is considered to be the most cost-effective, field-proven technology. The equipment and design methodologies for this technology are readily available. In addition, it requires the least capital for installation, and is relatively much simpler than any other technology for application to Army facilities without further modification (Table 21).

A diurnal cycle cold storage system is recommended as an ideal Army energy storage demonstration project. To proceed with such a project, the following steps should be taken:

1. Select an Army facility with appropriate building thermal loads, climatic conditions, utility rate structure, and space for equipment installation.

2. Confirm the building load characteristics through field instrumentation.

3. Design and install a prototype system.

4. Monitor the system to confirm the design methodology and to document the energy savings and economics.

5. Develop guidelines to evaluate the potential of installing diurnal cooling systems at other installations.

METRIC CONVERSION FACTORS

°C	= (°F - 32) (5/9)
1 psi	= 703.070 Kg/m^2
1 gal	= 3.785 L
1 sq ft	= .0929 m^2
1 ton (short)	= .907 ton (metric)
1 in.	= 25.4 mm
1 ft	= .3048 m
1 lb	= .4535 Kg
1 Btu	= 1.055 kJ
1 mile	= 1.609 Km
1 cu ft	= .0283 m^3

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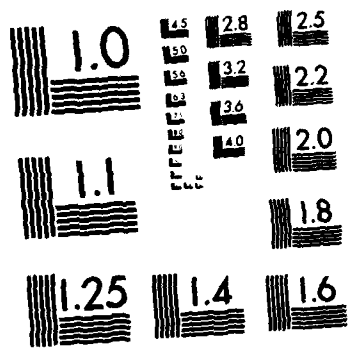

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